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# Feasibility of Rooftop Wind Turbines in Boston

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## **Rooftop Wind Turbine Feasibility in Boston, Massachusetts**

May 4, 2010

An Interactive Qualifying Project: submitted to the faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the  
Degree of Bachelor of Science

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This report represents the work of four WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirement. WPI routinely publishes these reports on its web site without editorial or peer review.

## **Abstract**

The Massachusetts Department of Energy Resources is committed to assessing new forms of renewable energy. This project determined the feasibility of rooftop wind turbines in Boston. We interviewed and consulted major stakeholders, and considered siting factors, turbine technology, economic feasibility and social reactions. Currently, rooftop wind turbines are not economically viable in Boston due to long payback periods resulting from siting challenges and underdeveloped technology. We recommend research into urban siting methods as well as vertical axis wind turbines.

## **Acknowledgements**

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Additionally, we would like to thank all of the wind turbine manufacturers and installers who answered our numerous questions and provided us information that was crucial to our project.

Finally, we thank our advisors, Professor Chrysanthé Demetry and Professor Richard Vaz, for their consistent feedback and support throughout this project. We would also like to thank our social science research professor, Professor Seth Tuler, who helped us hone our skills in performing research and writing the report.

# Executive Summary

Currently, our main energy sources are fossil fuels. Fossil fuels are a finite resource and a leading cause of pollution and environmental degradation. Therefore, it is vital that society switch to cleaner and more sustainable sources of energy, such as solar, wind, hydroelectric and geothermal. To help in developing and utilizing renewable sources of energy in Massachusetts, plans such as the Green Communities Act (GCA) have been put into action. The GCA requires that the state must increase its use of renewable energy by 1% each year. By 2020, the state must be using renewable energy to generate at least 20% of its electricity needs. The Massachusetts Department of Energy Resources (DOER) has taken on the task of finding and implementing possible renewable energy solutions in the state. We were asked by the DOER to determine the feasibility of rooftop wind turbines in Boston.

## Methodology

To determine the feasibility of rooftop wind turbines, we developed the following objectives:

- Determine the siting factors involved with the installation of rooftop wind turbines and determine how these factors affect the feasibility.
- Find the most important wind turbine attributes for urban environments and determine if any models currently on the market meet these attributes.
- Perform an economic analysis of the top turbine models currently on the market.
- Investigate the social concerns and motivations towards rooftop wind turbines in Boston.

We read through numerous feasibility studies of urban wind turbines to gain a better focus of what our project would entail. These studies helped us establish the siting criteria and performance analyses of small wind turbines by providing us with information on urban wind resources. We also investigated existing rooftop wind turbine installations, such as those at the Boston Museum of Science (MOS), Harvard University, and Boston City Hall. We investigated four siting factors: wind resources, zoning laws, structural integrity of roofs, and grid connection. We consulted a zoning specialist and a structural engineer to get information related to the restrictions on installing a rooftop wind turbine due to zoning laws and structural concerns. We also spoke with engineers from NSTAR, the electric utility company for Boston, to determine any limitations or complications that may come up with connecting to the electrical grid.

In order to compare available wind turbines to each other, we found several databases and came up with about 480 different models. We organized our comprehensive list into three categories of interest: vertical axis wind turbines (VAWTs), horizontal axis wind turbines (HAWTs) with 7-25 foot diameters, and HAWTs with 26-50 foot diameters. The list was narrowed down under the following criteria:

- Blade diameter: less than 50 feet (only for HAWTs)
- Power rating: 5-50 kW
- Cut in speed: less than 7 mph (3.1 m/s)
- Weight: less than 10,000 pounds

- Noise: less than 55 dB

Once this was done, we compared the remaining models based on their projected power production and rating as well as cut-in and production wind speeds.

In addition to the performance analysis, we created an economic analysis tool to determine the payback period of each model. This calculator takes into account the inflation rate of money over time and applicable incentives. It also provides a comparison to alternative investments such as a high yield savings account.

We also asked project managers what complaints they were receiving from the public and in the process discovered the social concerns and what motivations people had for installing rooftop wind turbines. We also interviewed three different real estate corporations: Hines, Massachusetts Convention Center Authorities, and Boston Housing Authorities. This allowed us to draw conclusions on motives for installing wind turbines as well as the requirements needed for real estate owners to consider installing rooftop wind turbines, such as payback period.

## Findings and Conclusions

Based on information from previous feasibility studies, our own analyses, and responses from interviews with key stakeholders, we developed the following findings and conclusions:

- **Siting is of great importance, since it can limit the performance of urban wind turbines by causing a low capacity factor.**

In many studies we found, the average capacity factor for rooftop wind turbines was 5%. This poor performance is currently a major factor limiting the feasibility of small urban wind turbines and is primarily due to inappropriate siting of the wind turbines. An urban environment contains turbulence caused by buildings and obstructions, and careful siting is required to avoid these less efficient winds. With proper siting, higher capacity factors can be achieved, making urban wind turbines more feasible. Capacity factors as high as 14% have been achieved in urban settings. Greater capacity factors are also possible considering that rural wind turbines see percentages in the 20-35% range and higher. These reasonable capacity factors provide a more assuring outlook for rooftop wind turbines.

- **Increases in capacity factor, price of electricity, and/or value of Renewable Energy Credits could make rooftop wind turbines more economically feasible in the future.**

The low capacity factor achieved in an urban environment is the main hindrance in rooftop wind turbine feasibility; however, it is not the only factor affecting it. The price of electricity and value of RECs also affect how much income is generated from energy produced with a wind turbine. These three factors have a significant impact on the economic feasibility of rooftop wind turbines. Using future projections for these factors, we determined that small increases in each of them could significantly reduce the payback period of rooftop wind turbines, making them more economically feasible.

- **Certain areas and building types are more promising for rooftop wind turbines.**  
We came to several conclusions regarding the most suitable locations for installing rooftop wind turbines. Buildings that meet the following criteria would be easier and more effective to install rooftop wind turbines:

- Above 150 feet tall, and taller than buildings upwind
- Roof area of at least 5,000 square feet
- Supported by columns to which the turbine can be mounted
- Not close to historic districts, residential areas, or avian habitats
- In a commercial, waterfront, or industrial area
- Connected to either a spot or radial network

- **A variety of existing wind turbines could produce a substantial amount of energy in an urban environment.**

Although many small wind turbines suffer poor performance in an urban environment, there are several which are suitable for power production on a rooftop, shown in Table 1.

Type	Manufacturer	Rating (kW)	Calculated Annual Production (kWh)	Cut-in Speed (mph)	Production Speed (mph)
VAWT	Venco Power GmbH	50	N/A	5.6	26.8
	Windports	20	N/A	5.6	32.44
	UrbanGreenEnergy	10	N/A	4	12
HAWT (7-25 ft diameter)	A&C Green Energy	10	5,562	6.7	24.6
	Altem Power	10	5,386	5.6	24.6
	Aeolos Wind Energy	10	5,386	6.7	22.3
HAWT (26-50 ft diameter)	Hannevind	22	15,454	4.4	20
	Nanjing Supermnn Industrial	50	15,454	6.7	26.8
	Aventa Ltd	6.5	14,443	4.47	13.4

*Table 1 - Top turbine models*

- **There does not seem to be a strong public attitude for or against rooftop wind turbines, and there are multiple motivations for installing rooftop wind turbines.**  
The social opposition against large-scale wind turbines has not been seen towards rooftop wind turbines, probably because they are so rare. However, this is likely to change if more installations are built. We believe that the most significant future social concerns would be linked to aesthetics, noise and visual flicker. The main motivation for alternative energy is for power production, yet most current rooftop wind turbines are intended to demonstrate the use of renewable energy and educate the public about wind power.

## Recommendations

We believe that rooftop wind turbines have the potential to become feasible in the future, and that the Department of Energy Resources can play a role in promoting their development. We present the following recommendations:

- **Perform testing on small wind turbines, especially VAWTs, to determine their performance in urban environments.**  
Vertical axis wind turbines are theoretically better in the turbulent conditions that are common in urban locations. More urban testing will provide more information needed to gain a better understanding of this technology and improve their development. Further testing would also bring upon more accurate wind data and improved siting methods.
- **Maintain a database of all available small wind turbines.**  
The database we have compiled can serve as a basis for a list that should prove valuable in selecting wind turbines for potential projects. This database provides vital information regarding what makes a wind turbine most suitable for a specific site such as datasheets and testing results.
- **Work with the Small Wind Certification Council and other organizations to develop a standardized method of establishing and verifying power ratings and curves.**  
Many manufacturers' data is inaccurate and/or optimistic. Standardizing power ratings, power curves, and other data will help provide a reliable method of measuring wind turbine power output accurately and comparing this output with those of other wind turbines.
- **Provide assistance to individuals or organizations interested in installing rooftop wind turbines by helping them locate and assess potential sites.**  
Our report contains siting advice that could help improve the success rate of wind turbine installations in Boston. By providing assistance, people would be more likely to invest into wind turbines and feel more confident about it. This could lead to an increased number of rooftop wind turbine installations that are more effective.
- **Offer information to the public on what incentives are available.**  
This will likely help make the public more aware of the financial help available to them and is likely to increase the number of installations, along with helping people cover the costs of buying and installing rooftop wind turbines.



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3.5	Ryan	John
4 Findings	Mario, Arnold	John
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4.2	Mario	John
4.3	John	Mario
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Most of the above sections were previously written and were written and edited by multiple team members. For the final report we mention the primary author and primary editor. Once the report was compiled each team member edited the entire draft. We then compared edits and finalized the paper.

# Table of Contents

<b>Abstract .....</b>	<b>i</b>
<b>Executive Summary .....</b>	<b>iii</b>
<b>Table of Figures .....</b>	<b>x</b>
<b>Table of Tables .....</b>	<b>xi</b>
<b>List of Acronyms .....</b>	<b>xii</b>
<b>1 Introduction .....</b>	<b>1</b>
<b>2 Background.....</b>	<b>2</b>
<b>2.1 Renewable Energy.....</b>	<b>2</b>
<b>2.2 Renewable Energy in Massachusetts.....</b>	<b>3</b>
<b>2.3 Wind Turbine Technology .....</b>	<b>4</b>
2.3.1 HAWT vs. VAWT .....	4
2.3.2 Theoretical Power Production .....	6
2.3.3 Power Conversion Methods: Generators and Power Electronics.....	7
<b>2.4 Economic Aspects of Turbines .....</b>	<b>8</b>
<b>2.5 Siting Factors.....</b>	<b>8</b>
2.5.1 Wind Resources.....	8
2.5.2 City Regulations and Zoning.....	9
2.5.3 Structural Integrity of Roofs.....	9
2.5.4 Interconnection to Electrical Grid.....	10
<b>2.6 Social Concerns.....</b>	<b>11</b>
<b>3 Research Methods .....</b>	<b>13</b>
<b>3.1 Siting of Rooftop Wind Turbines in Boston.....</b>	<b>13</b>
<b>3.2 Analysis of Rooftop Wind Turbine Attributes.....</b>	<b>14</b>
<b>3.3 Analysis of Rooftop Wind Turbine Economics .....</b>	<b>16</b>
<b>3.4 Social Concerns and Motivations to Rooftop Wind Turbine Installations .....</b>	<b>17</b>
<b>3.5 Integrative Analysis .....</b>	<b>18</b>
<b>4 Feasibility Findings.....</b>	<b>20</b>
<b>4.1 Site Study of Boston .....</b>	<b>20</b>
4.1.1 Wind Characteristics in Boston.....	20
4.1.2 Regulations and Zoning Laws in Boston .....	23
4.1.3 Structural Integrity of Roofs.....	24
4.1.4 Grid Interconnectivity.....	25
4.1.5 Integrative Siting Map.....	26
<b>4.2 Comparison of Rooftop Wind Turbine Models .....</b>	<b>27</b>
<b>4.3 Economic Analysis of Rooftop Wind Turbines .....</b>	<b>32</b>
4.4.1 Social Concerns of Rooftop Wind Turbines in Boston.....	38
4.4.2 Social Motivations for Installing Rooftop Wind Turbines.....	39
<b>5 Conclusions and Recommendations .....</b>	<b>41</b>
<b>5.1 Conclusions.....</b>	<b>41</b>
<b>5.2 Recommendations.....</b>	<b>42</b>

<b>Bibliography .....</b>	<b>44</b>
<b>Appendix A: Generator Types and Efficiency .....</b>	<b>47</b>
<b>Appendix B: Siting Map Layers .....</b>	<b>48</b>
<b>Appendix C: Wind Turbine Models .....</b>	<b>53</b>
<b>Appendix D: Wind Speed at Different Elevation Calculation Method .....</b>	<b>60</b>
<b>Appendix E: Economic Analysis Methods .....</b>	<b>62</b>
<b>Appendix F: Districts in Boston Allowing Rooftop Wind Turbines .....</b>	<b>64</b>
<b>Appendix G: Interview Questions .....</b>	<b>66</b>
<b>Appendix H: Interview Notes .....</b>	<b>69</b>
<b>Appendix I: Team Assessment.....</b>	<b>79</b>

## Table of Figures

Figure 1 - US energy use by source, 2008 .....	2
Figure 2 - Two bladed HAWT .....	5
Figure 3 - VAWT designs from left to right: H-rotor, Savonius, and Darrieus turbine .....	5
Figure 4 - Distributed system designs.....	10
Figure 5 - Boston Annual Wind Speeds at 70 meters .....	21
Figure 6 - Wind flow over a building .....	21
Figure 7 - Integrative Map of Boston Siting Factors .....	26
Figure 8 - Warwick wind trial power curve.....	29
Figure 9 - Factors taken into account when evaluating economic viability. ....	32
Figure 10 - Government incentives taken into account in economic calculator.....	33
Figure 11 - Net present value of a wind turbine investment compared to a savings account investment .....	34
Figure 12 - Net present value given varying capacity factors .....	35
Figure 13 - Net present value with varying electricity costs .....	36
Figure 14 - Net present value given varying REC prices .....	37
Figure 15 - Net present given an increase in capacity factor, price of electricity, and price of RECs .....	38
Figure 16 - Reasons for installing urban wind turbines.....	39

## Table of Tables

Table 1 - Top turbine models.....	v
Table 2 - HAWT vs. VAWT comparison.....	6
Table 3 - Comparison of generators.....	7
Table 4 - Noise regulations in Boston.....	23
Table 5 - Top turbine candidates based on theoretical performance .....	31
Table 6 - Payback periods and assumptions in the calculations for Figure 11 .....	34
Table 7 - Payback periods and assumptions in the calculations for Figure 12 .....	35
Table 8 - Payback periods and assumptions in the calculations for Figure 13 .....	36
Table 9 - Payback periods and assumptions in the calculations for Figure 14 .....	37
Table 10 - Payback periods and assumptions in the calculations for Figure 15 .....	38
Table 11 - Current and future economics overview.....	41

## List of Acronyms

**AWEA** – American Wind Energy Association  
**BHA** – Boston Housing Authority  
**BLC** – Boston Landmarks Commission  
**BRA** – Boston Redevelopment Authority  
**BUWT** – Building-mounted Urban Wind Turbine  
**CEC** – Clean Energy Center  
**DOE** – Department of Energy  
**DOER** – Department of Energy Resources  
**DG** – Distributed Generation  
**EIA** – Energy Information Administration  
**FAA** – Federal Aviation Authority  
**HAWT** – Horizontal Axis Wind Turbine  
**IEEE** – Institute of Electrical and Electronics Engineers  
**MCCA** – Massachusetts Convention Center Authority  
**MOS** – Boston Museum of Science  
**MTC** – Massachusetts Technology Collaborative  
**NCDC** – National Climatic Data Center  
**NIMBY** – Not in my backyard  
**REC** – Renewable Energy Credit  
**RPS** – Renewable Portfolio Standard  
**SWCC** – Small Wind Certificate Council  
**UL** – Underwriters Laboratories  
**VAWT** – Vertical Axis Wind Turbine

# 1 Introduction

Currently global energy use is at a record high and continues to increase. In the US, more than 85% of energy is obtained from fossil fuels (US DOE, 2010). Given their very slow production rate and the rapid consumption, fossil fuels are essentially finite in quantity. Predictions on the amount of time they will last for range from 42 to 102 years (Shafiee & Topal, 2009). Most scientists also agree that fossil fuels cause pollution and have a harmful impact on the environment (Lvovsky, Hughes, Maddison, Ostro, & Pearce, 2000). To avoid problems in the future, we must turn to energy sources such as solar panels and wind turbines that are renewable and environmentally friendly sources.

Massachusetts is making an effort to promote the use of renewable energy with acts such as the Green Communities Act (GCA) which aims to have 20% of the state's electric energy load produced through renewable sources by 2025. Massachusetts currently has several renewable energy installations throughout the state, including wind, hydro, and solar installations, but it must continue to increase its renewable capacity to fulfill the GCA requirement. One organization within Massachusetts that is working to maximize development of all renewable energy sources is the Department of Energy Resources (DOER). Among other sources, the DOER is currently interested in the possibility of rooftop wind turbines in Boston, due to the city's abundant coastal wind resources and large electrical loads. Rooftop wind turbines may be a solution for a dense, urban area where the open land required for larger wind turbines is nonexistent.

All around the world, large wind farms in rural areas and off ocean shores are producing large amounts of energy. These areas are prime locations for wind turbines due to the high wind speeds and distance from populated areas. There is a considerable amount of documentation on the importance, benefits, and challenges concerning large-scale wind turbines. Currently, the wind industry is exploring the use of small-scale wind turbines. However, since this is a new development, little research has been done on their performance. Rooftop wind turbines in urban environments present unique challenges. The quality of wind in an urban environment is complex due to many obstructions in the wind's path. Additionally, connecting rooftop wind turbines to varying types of electrical grid networks is challenging. There is also limited information on the social views towards rooftop wind turbines since they are not yet common enough for any opinions to have been formed. The limited information on rooftop wind turbines in urban environments makes it difficult to assess their value within the renewable energy market.

The goal of this project was to determine the feasibility of rooftop wind turbines on buildings in Boston. We accomplished this by taking into account the siting, economic, technical, and social factors of rooftop wind turbines. The siting factors included aspects such as wind resources, zoning regulations, structural integrity of roofs, and connection to the grid. Our technology investigation explored the performance of wind turbines and which types of turbines would be most suitable for an urban environment. An economic analysis was performed to determine whether or not rooftop wind turbines would be a worthy investment. Finally, we explored reactions that exist towards wind turbines and reasons for installing rooftop wind turbines. After examining these factors, we performed an integrative analysis to develop conclusions regarding the overall feasibility of rooftop wind turbines. It is our sincere hope that this work will assist the DOER in determining if rooftop wind turbines in Boston are currently a viable source of renewable energy, or if not, what could make them more practical in the future.

## 2 Background

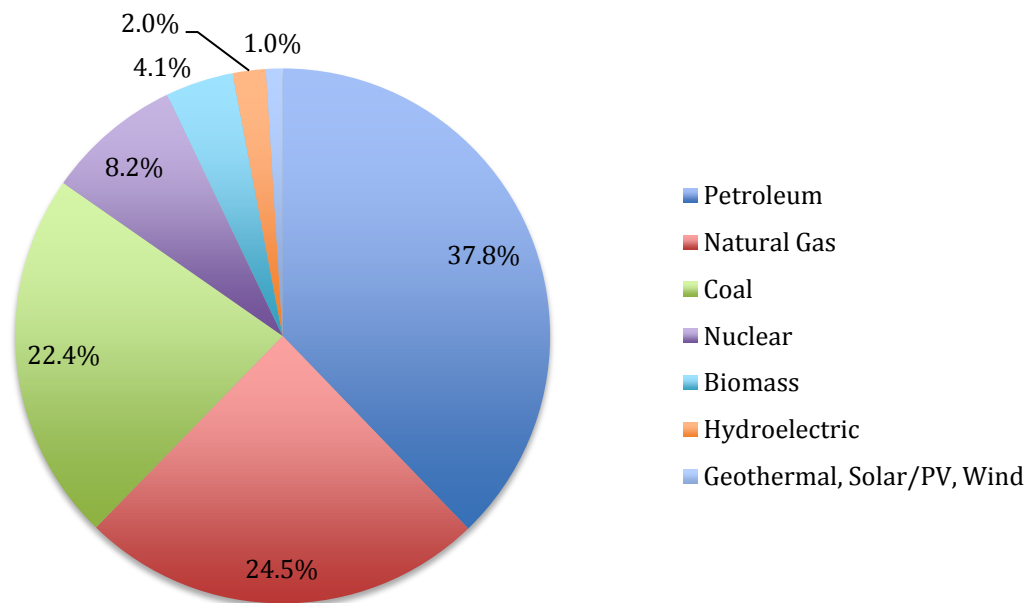
We begin this chapter with an overview of why wind power is a viable source of renewable energy. Then we discuss the technology used for wind turbines and present the social factors related to this project. Following this, we explain the siting factors involved in installing wind turbines, such as wind resources, zoning laws, structural integrity, and network interconnection.

### 2.1 Renewable Energy

There is a current shift towards the use of renewable energy that has started in response to the high global energy use and harmful environmental impact of current energy sources. The most common renewable energy sources currently used are solar, wind, and geothermal.

During the second half of the 20<sup>th</sup> century, the global population more than doubled. In response, economic activity has more than quintupled and energy use had quadrupled (Kates & Parris, 2003). The use of energy continues to rapidly increase as well as the population. The Energy Information Administration (EIA) predicts that the world energy use will increase 44% from the 2006 energy use by 2030 (US EIA, 2009). This steady increase of use is difficult to sustain and current energy use relies heavily on the use of fossil fuels.

Today's world makes heavy use of electronics, combustion engines, and climate control systems, which depend on the use of fossil fuels. As seen in Figure 1, the U.S. produced 84.7% of its energy from fossil fuels in 2008, with petroleum producing 37.8% of the total energy and renewable sources producing only 7% (US EIA, 2008).



*Figure 1 - US energy use by source, 2008 (US EIA, 2008)*

One problem with using fossil fuels and nuclear power for energy production is that they are finite sources. One study estimates that petroleum, natural gas, and coal will be exhausted in



approximately 35, 37, and 107 years respectively (Shafiee & Topal, 2008). In order to meet increasing energy needs in the future, the use of renewable energy needs to be increased. If renewable energy sources are not incorporated into the overall energy use, there will likely be an energy crisis during which the needed energy is not available due to exhausted fossil fuels and lack of other energy sources.

A second problem with the use of fossil fuels is their harmful impact on the environment. When fossil fuels are burned, they release greenhouse gases, such as carbon dioxide and toxins that are harmful to humans, plants, and animals. Natural elements, such as trees and the ocean, absorb only about half the amount of carbon dioxide produced by burning fossil fuels, which the Global Carbon Project estimates to be about 8,700 million tons of carbon dioxide per year as of 2008 (GCP, 2009). This excess amount of carbon dioxide and greenhouse gases continues to increase and has a major influence on the global climate. Increases in carbon dioxide and greenhouse gases cause the average surface temperature of the earth to increase, intensified storms, sea levels to rise, and other climatic changes to occur (Houghton et al., 2001). These climate changes have the potential to drastically alter ecosystems and cause species to become extinct.

Due to the steady increase in global energy consumption, depletion of fossil fuels, and concerns for the environment, there has been an increased interest in the development of renewable energy sources. The main sources of renewable energy are biomass, hydro electrical, solar, wind and geothermal, which supplied 14% of the total global energy use in 2001 (Demirbas, 2005). The use of renewable energy continues to increase and must do so to provide for the overall energy demand in the future. Wind power has seen a significant increase since it was originally used for power production. In 1990, the global energy capacity from wind power was 2,000MW, and by 2000 it had increased to 20,000MW (Demirbas, 2005). This shows that wind power has the potential to be a large source of renewable energy, and so is worth pursuing.

## **2.2 Renewable Energy in Massachusetts**

Currently, most of Massachusetts' power is produced by fossil fuel burning plants. However, state and local authorities such as the Massachusetts Department of Energy Resources (DOER) have made it their goal to promote the use of renewable and sustainable forms of energy. This goal has led to the installation of renewable energy based power producing units throughout the City of Boston and across Massachusetts. These projects range from the installation of two 600kW wind turbines at Deer Island, to smaller rated solar energy panels installed on rooftops throughout Boston (EES, 2008).

The DOER plans to implement the Energy Efficiency Investment Plan that could potentially save \$6 billion and up to 30,000GWh in lifetime energy (MA DOER, 2010a). The DOER hopes this plan will meet all the increased demand while providing a constant supply of electricity to the residents of the state.

There are other plans that have been implemented to help increase and diversify renewable energy use in the state. One such plan is the Green Communities Act (GCA) that was passed by the Massachusetts legislature and signed in by Governor Deval Patrick in July 2008. The GCA was enacted into law, to lay guidelines to help Massachusetts meet its renewable energy and energy efficiency targets. Under the Green Communities Act, municipalities are able to develop renewable energy resources and facilities, create employment from the development of these

facilities and reduce energy consumption and pollution (Massachusetts, 2008). Some of the energy targets of the GCA include:

- Produce at least 20% the state's electricity using renewable energy by 2020,
- Reduce energy consumption in the state by 10% by 2017, and
- Decrease the fossil fuel use by 10% from 2007 levels by 2020 (Massachusetts, 2008).

To help achieve these energy targets, the Renewable Portfolio Standard (RPS) was established. The RPS is designed to augment the state's use of renewable energy and helps promote the use of clean energy sources (RET, 2010b). To help fulfill the requirements of the RPS, Renewable Energy Certificates (RECs) are awarded based on power produced. One credit is given per megawatt-hour of electricity generated, and can be sold at market value, which changes with demand (RET, 2010a). To calculate the RECs, the New England information system (NE-GIS) has been adopted (RET, 2010a). The NE-GIS keeps track of information on New England's power system including its operations and capacity and is used to determine the power output of renewable energy in Massachusetts.

There are numerous incentives offered for renewable energy projects in Massachusetts. One of the most prominent is the abovementioned Renewable Energy Credits, which help fulfill the requirements of the Renewable Portfolio Standard. Other incentives in Massachusetts offer 100% deductions on excise tax, sales tax, and property tax for investing in renewable energy (DSIRE, 2009). There are also several major incentives offered on the federal level. The largest of these is the Federal Investment Tax Credit, which offers tax credit equal to 30% of all initial costs for the project. The other large federal incentive offered is the Production Tax Credit, which rewards renewable energy production with 2.1¢/kWh of energy generated (DSIRE, 2009).

Amid all the renewable sources of energy, wind energy has emerged as an efficient alternative in Massachusetts that has led to the distribution of numerous grants to various wind projects around the state (MA CEC, 2010). The reason for this emergence is because of favorable wind conditions as well as a drive to find alternative energy sources to the currently conventional fossil fuels. Consequently, Massachusetts hopes that wind energy will play a significant role in a promoting clean energy future. To this end, one of the goals set for the development of wind energy in the state is the installation of 2000 megawatts of wind capacity, by 2020 (MA DOER, 2010b).

## **2.3 Wind Turbine Technology**

The wind turbine industry has seen drastic alterations in the technology used since its first use for electrical production in the 1980s. The airfoil types, generators, and power electronics used in wind turbines have all seen major improvements. These improvements on the larger wind systems have been passed down to small-scale wind turbine technology.

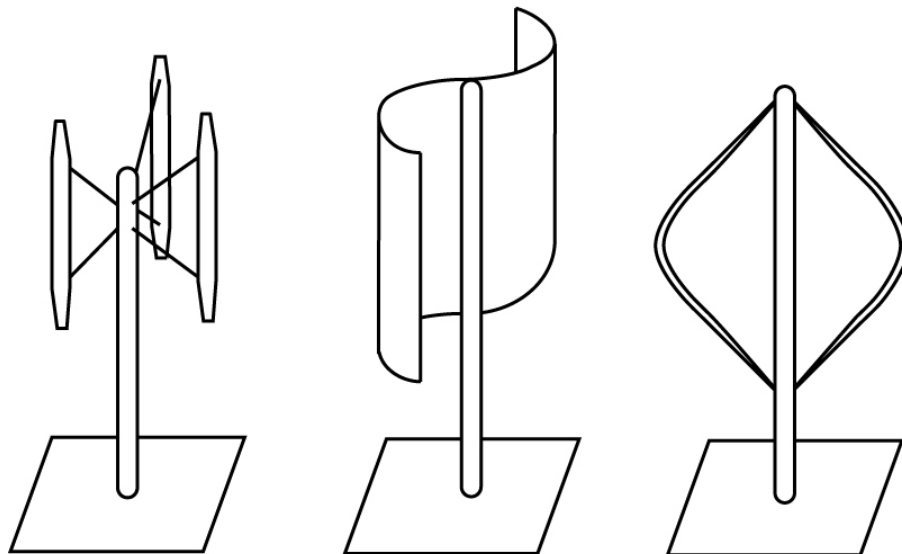
### **2.3.1 HAWT vs. VAWT**

There are two main types of wind turbines, with the difference being in the orientation of the blades. Horizontal axis wind turbines (HAWT) are the more common type shown in Figure 2.



*Figure 2 - Two bladed HAWT (used with permission from Menet, 2000)*

Vertical axis wind turbines (VAWT) are less common and come in many different varieties. The three most popular VAWT designs, H-rotor, Savonius, and Darrieus, are depicted in Figure 3 (Eriksson, Bernhoff, & Leijon, 2006).



*Figure 3 - VAWT designs from left to right: H-rotor, Savonius, and Darrieus turbine*

HAWTs are more conventional since they are currently more efficient in converting wind flow into electricity (Howell, Qin, Edwards & Durrani, 2009). However, HAWTs require that the wind be laminar. In laminar flow, the layers of wind are steady and parallel to each other with no disruption between them. In turbulent wind flow, the layers of wind are chaotic and change direction and pressure suddenly. VAWTs are theoretically superior to HAWTs because VAWTs can harness the wind flow coming from any direction and do not need to yaw into the direction of the wind.

There are three costs involved that vary between the two types of turbines: the cost of manufacturing the blades, the cost of a mast, and the cost of the foundation. HAWTs generally have the lowest cost in terms of blade production, while VAWTs have generally higher blade manufacturing costs, due to the complexity in design and material use. In addition, VAWTs usually require more elaborate foundations because the dynamic loads are more challenging to counter. Due to all these factors, VAWTs tend to have a higher cost (Eriksson et al., 2006).

Table 2 gives an overview of the differences between HAWTs and VAWTs. It is important to take into consideration that HAWTs have had many years of development and VAWTs have only seen recent development. There are claims that if VAWTs were to see more development, their efficiency and cost would match and possibly surpass HAWTs in the urban environment (Eriksson et al., 2006).

Type	Pros	Cons
HAWT	<ul style="list-style-type: none"> <li>• Efficient</li> <li>• Low cut in speed</li> <li>• Low manufacturing cost</li> </ul>	<ul style="list-style-type: none"> <li>• Requires laminar wind flow</li> <li>• Requires yawing mechanism</li> </ul>
VAWT	<ul style="list-style-type: none"> <li>• Works in turbulent wind flow</li> <li>• Potential for improvements</li> </ul>	<ul style="list-style-type: none"> <li>• Less efficient</li> <li>• High cut in speed</li> <li>• High manufacturing cost</li> </ul>

*Table 2 - HAWT vs. VAWT comparison*

### 2.3.2 Theoretical Power Production

The power produced by wind turbines is largely dependent on the area swept by the blades and the power coefficient of the blade design. The power coefficient is limited to a maximum of 0.593, which is commonly known as the Betz limit (Polinder, van der Pijl, de Vilder, & Tavner, 2005). This means the turbine cannot capture more than 59.3% of the kinetic energy from the wind swept by the area of the blades can be converted into energy. This is because if all the energy were taken from the wind, it would no longer be moving, so it could not exit the wind turbine's blade area to allow more wind to enter. The power coefficient, or aerodynamic efficiency, is the ratio between the wind speed and the speed of the tip of the blade. For HAWTs, the power increases with the square of the blade radius, and altering pitch and using the nominal amount of blades increases the power coefficient. For HAWT designs, the aerodynamic efficiency increases only minimally after three blades. A three blade HAWT design produces a power coefficient 5% higher than that of a two-blade design (Patel, 2006).

VAWTs vary greatly in design. Increasing the blade height and the amount of blades does increase the power produced, but the correlation is far more complicated than for HAWTs. An article that describes the power equations used for both the Savonius and Darrieus turbines explains that they have far more variables than the HAWT designs, such as the angle of the blade to the axle (Menet, Valdès, & Ménart, 2000). Various articles present the aerodynamic characteristics of VAWTs through the use of calculations and theoretical models. One such article presents three Darrieus designs that are compared using numerous complex equations (Islam, Ting, & Fartaj, 2006). Another article looks at the airflow of an H-rotor turbine using 2D and 3D modeling and the physics involved (Howell et al., 2009). However, these articles were

very technical and did not provide a substantial amount of information that was relevant to our project.

We were able to find only one actual test of a VAWT versus a HAWT. In Ashendon, UK, a 6kW HAWT and a 6.2kW VAWT were installed on the same roof and tested for a year. The results indicated the HAWT outperformed the VAWT; the VAWT had issues at low wind speeds during which it used electricity, instead of producing it. The trial conclusion stated the specific VAWT would no longer be used; however, it is still not conclusive if VAWTs could potentially outperform HAWTs with proper technology improvements (Ashenden Wind Trials, 2009).

### 2.3.3 Power Conversion Methods: Generators and Power Electronics

In order to export energy to a grid from a wind turbine, the mechanical energy is first converted to electrical energy via a generator. The output of the generator must then be converted to match the power grid the wind turbine is connected to, with power electronics. Power electronics consist of solid-state electronics, which are used to control and convert electric power.

Power grids handle alternating current (AC), which means the current changes direction. Direct current (DC) flows in one direction and is used in electronic devices. AC is used for power grids since it can travel farther distance with fewer losses than DC and the magnitude of its voltage can easily be modulated. Within the US, AC power reaches people's homes at a frequency of 60 Hz. Power electronics are commonly used to connect generators to the grid's power; either a DC-to-AC inverter or an AC-to-AC transformer is used depending on the generator used. Power electronics are also used to monitor the power output and quickly disconnect the wind turbine from the grid, if the power is inadequate or of poor quality.

There are three main types of generators that are potential candidates for a wind turbine: DC generators, synchronous generators, and induction generators. Commercial small wind turbines use DC generators due to their low cost (Patel, 2006). Table 3 summarizes the common differences between the generators, which are further explained in Appendix A.

Type	Pros	Cons
DC	<ul style="list-style-type: none"> <li>• Low manufacturing cost (under 100kW)</li> <li>• Suited for variable wind speeds</li> </ul>	<ul style="list-style-type: none"> <li>• High maintenance cost</li> <li>• Poor efficiency</li> <li>• Requires inverter</li> </ul>
Synchronous (AC)	<ul style="list-style-type: none"> <li>• Easily connected to electrical grid</li> <li>• Functions at low wind speeds</li> </ul>	<ul style="list-style-type: none"> <li>• Not suited for variable wind speeds</li> <li>• High maintenance cost and use cost</li> <li>• Requires external excitation</li> </ul>
Induction (AC)	<ul style="list-style-type: none"> <li>• Suited for variable wind speeds</li> <li>• Low maintenance and use cost</li> </ul>	<ul style="list-style-type: none"> <li>• Often requires gearbox</li> <li>• Requires converter</li> </ul>

*Table 3 - Comparison of generators*

## 2.4 Economic Aspects of Turbines

Using alternative energy, especially wind power, may not seem like it is cost-effective due to its high initial cost, so an economic assessment must be done to establish the commercial viability of a project (Ozerdem, Ozer, & Tosun, 2006). Developers of the technology as well as potential installers would all be interested in knowing the breakdown of the money being spent – what it's going towards and what kind of return is expected.

The cost of generating electricity in a wind farm has three main components: capital cost, operation and maintenance costs, and financing cost (Ozerdem et al., 2006). Capital cost consists of all initial investments made in purchasing the wind turbine and installing it. Operation and maintenance covers any routine expenses required to keep the turbine functioning properly. Financing cost is the money required to pay back all loans used to finance the project. Other important values to consider are the payback period and the net present value. Payback period is the amount of time for profits or benefits granted by the project to equal the initial investment. Net present value is simply the present value of the benefits minus the costs. In the case of wind turbines, benefits would be the money saved by producing energy. This makes net present value a good indicator of how profitable a particular investment is at any particular point in time.

Stakeholders are also likely to be interested in renewable energy sources that promise effectiveness, direct benefits, reduced risk, and are simple (Farhar & Houston, 1996). Potential customers would want the system to be effective so that it actually produces a sufficient amount of energy and be worth their money. They also like to know that they are making a difference and a smart investment by using renewable energy sources (Wiser, 1998). An economic analysis can provide these figures to determine the results of an investment in a rooftop wind turbine installation.

## 2.5 Siting Factors

Siting is an important aspect of wind turbine installation since it plays a major role in performance. In order to determine the feasibility of rooftop wind turbines, the issues concerning placement in an urban environment must be considered. In this section, we first discuss the role of wind resources, followed by a description of Boston's zoning laws. We then present the rooftop structural integrity considerations that need to be taken into account regarding wind turbine installation. Finally, we describe the grid connection challenges that are posed by the current utility grid networks and the regulations that protect them.

### 2.5.1 Wind Resources

The available wind resource plays a major role in finding locations to place wind turbines because without proper wind conditions, wind turbines cannot function effectively (Ozerdem et al., 2006). The *cut-in speed*, or the minimum wind speed for a wind turbine to produce power, ranges from 1.8 m/s (4 mph) to 4 m/s (9 mph) for small wind turbines. If the average wind speed in a particular location falls below this cut-in speed, a wind turbine in this location is likely to not generate useful amounts of energy.

Large-scale rural wind farms are able to harness the most useful and strongest winds at high elevations in large open areas, but urban wind resources are not as effective. Compared to rural locations, suburban areas have wind speeds that are 13-20% lower, and urban areas 29-40%

lower (Dutton, Halliday, & Blanch, 2005). The power produced by a wind turbine is proportional to the cube of the wind speed; therefore, these reductions could cause significantly lower power production. The equation used to calculate power from the wind can be found in Section 4.2.

It should be taken into account that wind speeds increase as altitude increases (Dutton et al., 2005). Wind speed at a specific altitude can be calculated using standard equations with a reference speed at a specific height. These equations can be found in Appendix D.

The *capacity factor* of a wind turbine is the ratio of its power produced compared to its output if it had been produced its rated power. In rural environments, the capacity factor ranges between 20-40% (RERL, 2005). A main cause for the capacity factor to decrease in an urban environment is turbulent wind conditions, which are less effective for wind turbines. Turbulence occurs when there are obstructions in the wind path, such as nearby buildings. The wind must flow around the obstructions, causing erratic changes in direction and wind speed. To avoid this problem, one study suggests that the roof where the turbine is to be located should be approximately 50% higher than any surrounding objects (Cace et al., 2007).

### **2.5.2 City Regulations and Zoning**

Zoning laws are put in place to protect the wellbeing of the public by regulating the use of land. These regulations can restrict or impose specifications on construction, including what can be added to roofs, including rooftop wind turbines.

In Massachusetts, on-shore wind turbine installations are governed in part by the zoning laws developed by the Boston Redevelopment Authority (BRA). These regulations restrict both the height and the noise that can be produced by a wind turbine. Height may prove to be a concern in regards to installing wind turbines, especially on a rooftop. Noise limits must also be followed in order to not disturb nearby areas, although noise limitations often vary with location. The Federal Aviation Administration (FAA) is also concerned with the height of objects and has set height restrictions. The FAA is specifically concerned with structures that may affect airspace, especially near airports, such as Logan International Airport in Boston. The FAA is also concerned with electromagnetic interference (EMI) that may cause interference with radio and communication equipment that rooftop wind turbines may be in close proximity to. The movement of the turbine blades can cause EMI, which could interfere with transmitted signals (Patel, 2006).

### **2.5.3 Structural Integrity of Roofs**

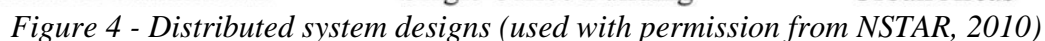
The structure of a rooftop should be looked at to ensure that a wind turbine installation would not compromise the integrity of a rooftop or building in any way. There are a number of roof top attributes that should be considered when installing wind turbines such as roof material, roof support and durability.

First it is important to acknowledge the different loads caused by a rooftop wind turbine: static and dynamic loading. *Static loading* is the dead weight of the turbine, tower and foundation. *Dynamic loading* is the force created by the wind pushing the turbine, which adds stress to the foundation. The varying torque caused by the moving blades also causes vibration, which needs to be considered when forming the foundation (Shaw, McClelland, & Rosen, 2009).

There are many materials that are used to construct roofs. These can include materials such as shingles, sheet metal and concrete. Each of these materials can support different loads and

Also, as a roof and the building that it's on ages this can pose additional challenges in installing a wind turbine. These challenges normally arise from the gradual degeneration of rooftops over time. This problem is generally encountered in older houses and buildings whose roofs cannot handle heavy additional structures.

There are three types of networks: radial, spot, and area, as shown in Figure 4. Each network has varying accessibility regarding connection of DG with radial networks being the most accessible and area networks the least accessible.



10



loads (NSTAR, 2010). Finally, area networks consist of a substation that connects to multiple network protectors which powers interconnected network transformer vaults. These interconnected transformer vaults are used in case one breaks down, so back-up power can be provided.

*Network protectors* are currently the biggest hurdle in connecting DG to a spot or area network since they “are not designed to connect [DG] and will result in equipment failure” (NSTAR, p. 7, 2010). Found in spot and area networks, they only allow power to flow from the network to the load, and will be tripped open if any power is sensed flowing the other way. Because of this, there are restrictions to be followed when connecting a source of energy, such as a wind turbine, to avoid tripping the network protectors and causing problems on the electrical network.

## **2.6 Social Concerns**

Studies have shown that groups opposing wind turbines cite aesthetics, noise pollution, and disruption of local wildlife as the most important issues (Kempton, Firestone, Lilley, & Whitaker, 2005). In this section, we discuss these concerns as well as additional concerns that are present towards wind turbines.

### **2.6.1 Aesthetics**

Wind turbines are often visible from a long distance off because the poles that hold the turbine hub can be up to 100 meters in height. Some people dislike the appearance of wind turbines since they believe they spoil the scenery. Currently, the majority of the wind turbine projects in Massachusetts have been constructed in open regions or coastlines away from residential and commercial areas, meaning that there is little aesthetic detriment (AWEA, 2009). However, rooftop wind turbines present a challenge concerning aesthetics because the urban environment means the turbines are often going to be near residential or commercial areas. Even though the wind turbines under consideration for rooftops in Boston only have heights ranging from 5 to 35 meters, it is very likely that they will be seen either from the street or from neighboring buildings. This will prove to be a problem if enough people oppose placement of a wind turbine due to aesthetic reasons, because then the turbine will have to be sited at an entirely new location.

### **2.6.2 Noise Pollution**

Wind turbines can generate a large amount of noise, depending on the model and wind speeds they are operating in. This noise generated can become a larger problem when the wind turbine is sited near residential areas. At night, the ambient noise at specific site is often lower than during the day when the ambient noise is higher and noise created by a wind turbine is not as noticeable. In rural areas, the public is more likely to complain about the noise created from wind turbines since the ambient noise is low. In an urban area such as Boston, rooftop wind turbines may not be as much of a concern for noise pollution since they are typically small in size and high up on rooftops, putting them further away from any people that may be able to hear the noise.

### **2.6.3 Disruption of Local Wildlife**

Wind turbines can obstruct the flight path of birds and bats, potentially injuring or killing these animals. This unnatural obstruction in the ecosystem of birds and bats is generally frowned upon (Krohn & Damborg, 1999). Additionally, bat populations tend to be more affected by wind turbines, because the high-pressure zones created by the wind turbines can kill bats that fly within a couple feet of an operating wind turbine (Risser, Burke, Clark, English, & Gauthreaux, 2007). However, in an urban environment where the bird and bat populations may not be all that substantial, wind turbines may have a much less pronounced effect.

Human constructions and activities are responsible for the death of many animals. It has been recorded that annually at least 97 million birds die due to colliding into buildings, cars are responsible for close to 60 million birds per year, and it is estimated that wind turbines kill 200,000 to 370,000 birds per year (Risser et al., 2007). Based on these numbers, one might assume that wind turbines have little impact on total bird casualties compared to other causes. However, there are three important factors to consider. First, there is little information on bird and bat casualties from small wind. Second, the numbers do not take into consideration endangered or rare species deaths. If half the population of an endangered species is being killed versus a small fraction of a common species, the impact is far more significant. Finally, if there is an increase in wind turbine installations, there is the possibility that there will be far more bird and bat deaths (Risser et al., 2007).

Certain precautions can be taken to reduce bird and bat deaths. The key suggested alterations include slower rotational rates of the blades, tubular towers, and fewer places where birds can perch. Slowing down the rate of blade rotation will make the blades more visible to flying birds while the tubular towers provide less of an area for birds to perch on unlike lattice towers. Additionally, it is suggested that wind turbines be sited away from bird habitats and bird migration paths. (Risser et al., 2007) Avoiding avian habitats would decrease deaths by siting wind turbines in areas with low avian populations, meaning there are less birds to be affected by any wind turbine installations.

### **2.6.4 Other Social Concerns**

While appearance, noise pollution, and disruption of wildlife are major issues, other problems with wind turbines are sometimes brought up to oppose their construction. For example, the flicker effect created by the spinning blades of wind turbines may annoy some people. The AWEA claims that flicker is not a problem for small wind turbines because the high rotation speeds of the blades make the shadow essentially invisible (AWEA, 2008). Lightning strikes are another concern, but rooftop wind turbines are grounded and there are numerous systems in place to prevent electrical surges and damage; therefore, it is not a major concern (AWEA, 2008). Specifically in colder regions that see sub-freezing temperatures and snowfall, ice buildup might prove to be a problem and safety hazard for wind turbines. The added weight of ice can decrease the efficiency of a wind turbine or even cause malfunctions. If the blades continue to spin while covered in ice, the ice could be thrown off the blades, posing a major safety hazard to anything or anyone nearby, especially on a rooftop at a high elevation. However, the AWEA states, “the risk of damage from ice falling from a (large) turbine is lower than the risk of being struck by lightning” (AWEA, 2008).

### **3 Research Methods**

The goal of this project was to determine the feasibility of rooftop wind turbines in Boston. We looked at the different factors that could make rooftop wind turbines feasible now or in the future. Our overall goal was broken down into several research objectives, including the analysis of:

1. Siting factors,
2. Attributes of available wind turbines,
3. Economic analysis of available wind turbines, and
4. Motivations to install rooftop wind turbines.

The results of these different objectives were combined to get an overall picture of the feasibility of rooftop wind turbines using an integrative analysis. With this, we were able to determine the necessary criteria for rooftop wind turbines in Boston and identify how well current technology meets these criteria. In this chapter, we explain each of our objectives and how we came to conclusions for each.

#### **3.1 Siting of Rooftop Wind Turbines in Boston**

From our background research we identified several important siting factors, which were: wind characteristics, zoning regulations, structural integrity of roofs, and grid connection access. With these factors we formulated the following research questions to guide us in determining siting criteria:

- What general wind environment is present in Boston?
- How does the rooftop environment affect the available wind resource?
- What zoning laws need to be considered concerning rooftop wind turbines?
- What are the structural criteria that allow rooftop wind turbine installation?
- What are the requirements for rooftop wind turbines to connect to the electric grid?
- What buildings and/or locations in the city have grid connections that are easily accessible to connect wind turbines to?

To determine the factors involved with siting rooftop wind turbines in Boston, we read feasibility studies on small-scale wind turbines done in different types of sites. Several of these studies suggest criteria for siting urban wind turbines and also give some data regarding the performance of the wind turbines. We also interviewed project managers that have installed rooftop wind turbines within Boston including the Museum of Science and Harvard University. We used the feasibility studies and information from interviews with project managers to learn the siting factors that other studies and projects looked at.

In terms of wind characteristics at a location, we determined the obstacles on roofs and surrounding areas that cause turbulence, the elevation of the installation, and the wind speeds available based on the location within the city. We did this partially by referring to several wind speed maps of Massachusetts and wind speed data. Additionally, we found two studies on the subject; both gave the same explanation for the effect of buildings and other obstacles on the prevailing wind.

Zoning regulations can limit some features of rooftop wind turbines, which could rule out some of the more cost effective designs. We consulted a zoning specialist from the City of Boston to obtain bylaws of the restrictions specific to rooftop wind turbines. Zoning laws may restrict the height and noise produced from rooftop wind turbines. Different sites will have to abide to different laws, so this was considered later in the integrative analysis.

Roofs have many different designs and thus some are more capable of supporting an additional load such as a wind turbine. By consulting a structural engineer, we determined the types of roofs that could support rooftop wind turbines as well as the range of static and dynamic loads that a wind turbine will exert on a roof and how much a roof can handle.

Finally, grid interconnectivity issues were considered. Utility companies restrict where and how rooftop wind turbines can be connected to the electric grid, so we determined the network types that are the easiest to connect rooftop wind turbines to, as well as the areas with those types of networks. We interviewed engineers at NSTAR to figure out what the restrictions are to interconnectivity and what types of locations would be most suitable.

Once the details for wind characteristics, zoning regulations, structural integrity, and grid connection access were determined; we were able to figure out the criteria needed by a location to be feasible for installing rooftop wind turbines. We also formed a siting map using Google Earth based on these siting factors. We created layers for wind speeds at an altitude of 70 meters, grid types, historical locations, approved zoning districts, and avian habitats. We also included the locations of current wind turbine installations.

## **3.2 Analysis of Rooftop Wind Turbine Attributes**

We examined the criteria for rooftop wind turbines that would make them more feasible, and then applied these criteria to current small wind turbine models to find several of the most feasible models. This was done to examine which, if any, of the small wind turbine models on the market would meet these criteria for feasibility. In order to accomplish this, we based our research on the following research questions:

1. What are the theoretical performance limits for various types of wind turbines?
2. Which turbine characteristics are likely to provide better power conversion in an urban rooftop environment?
3. What are some examples of small wind turbines currently on the market or in development that meet these criteria?

There are hundreds of wind turbine designs, and knowing how each design fares in an urban environment is important. A large majority of the wind turbines currently on the market are horizontal axis wind turbines (HAWTs), and their performance is well documented. Information on the performance of HAWTs was found in numerous studies, as well as interviews with engineers who worked on rooftop wind turbine projects in Boston. Vertical axis wind turbines (VAWTs) on the other hand vary widely in design. Unfortunately, the performance of different types of VAWTs is not documented well, even less so in urban environments. However, we were able to find several studies that loosely addressed the issue of the theoretical performance of VAWTs.

There are many technical criteria for wind turbines, such as dimensions of the blades, performance in turbulent wind, and startup wind speed. However, some of these criteria are more

critical to the feasibility of the turbine than others. We examined previous studies' work in classifying technical criteria for wind turbines in urban environments. This gave us a broad initial list of criteria to examine more closely. Even though their experience was chiefly with rural wind turbines, several employees at the DOER helped us start off our list with criteria that apply no matter where the wind turbine is located, such as blade diameter.

Additionally, we interviewed several project managers and engineers from local urban wind projects about what technical criteria they looked at when choosing wind turbines and why. These projects were in different types of sites, as described in Section 3.1. This gave us information on how desired technical attributes may also change with location. This, combined with the fact that there weren't many installations, made us skeptical about any conclusions drawn from these interviews. Similar to our search of performance data the main challenge we ran into while researching preferred characteristics of rooftop wind turbines was the lack of information on VAWTs. Despite this, our research into other urban wind projects allowed us to get a rough idea of the preferred characteristics of HAWTs.

In order for rooftop wind turbines to be feasible, the wind turbines must meet the criteria that are applicable to the specific site in mind. We first established general criteria that we could use to find the most suitable models. The DOER requested in the initial project goal that models should produce between 5 to 50kW. As we interviewed various stakeholders and our research progressed we established our remaining criteria, such as using models with a cut-in speed below 7 mph. With these criteria in hand, we scoured online wind turbine databases, such as [allsmallwindturbines.com](http://allsmallwindturbines.com), [awea.org](http://awea.org), and [ecobusinesslinks.com](http://ecobusinesslinks.com), and compiled a list of all wind turbine models that met our criteria along with their technical specifications. This method had some flaws, since we could not locate all the models due to the vast amount of models available online. From the models that met our criteria we identified the most promising models based on their estimated power output, which we calculated using a standard method for calculating the energy harnessed by a wind turbine (SEW, 2009). The equation takes into account factors such as wind density and aerodynamic efficiency. The details of this equation can be found in Section 4.2. This calculation gave us a consistent measure of the output for our wind turbine models. With the predicted power, we were able to sort our list of turbines to find the top candidates. From the top candidates we compared turbines against one another using the following attributes:

1. Highest predicted power output
2. Lowest start-up speed
3. Lowest operating speed

These attributes were chosen because our research had shown that these are the most important areas to consider when assessing a wind turbine. The power output is of course essential if the turbine is to be used for power production, and lower start-up and operating speeds help guarantee that the turbine is producing power consistently. With the top turbines selected, we were able to perform an economic analysis on the models, as described in the next section, to determine if any of these models are economically feasible for rooftops.

### 3.3 Analysis of Rooftop Wind Turbine Economics

The economics are another important attribute in determining whether a wind turbine is feasible, because even if a wind turbine meets the requirements of the technical criteria, it may be too expensive to realistically consider. Economic analysis is a well-established area, and so we examined several basic economic analysis methods from economic articles and books in order to gain an initial understanding of the process. After this initial research, we decided to use payback period as our sole metric for economic feasibility due to the nature of our study as well as time constraints. With this in mind, we developed several research questions concerning payback period.

1. What payback periods are currently achievable by urban rooftop wind turbines?
2. What range of payback periods do building owners require from a wind turbine investment?
3. What can be done to reduce the payback period?

We reviewed economic analysis methods in several wind turbine feasibility studies, such as the “Microgeneration in New Zealand” (Mithraratne, 2009) and “Micro Wind Turbines in the UK” (Peacock, Jenkins, Ahadzi, Berry, & Turan, 2007). In addition to this, we examined the methods used in several economic calculators such as the “Bergey Cash Flow Model” (Bergey, 2009) and the “Danish Wind Energy Calculator” (DWIA, 2003). We learned from these sources that payback period requires the following information:

- Power produced by the turbine
- Cost of the turbine
- Expected lifetime of the turbine
- Cost of electricity
- Rate of inflation of US currency
- Amount provided by federal and financial incentives
- Cost of installation (including transportation, mounting, etc)
- Cost of yearly maintenance

The cost of the turbine and expected lifetime were obtained on a turbine-to-turbine basis from the manufacturer. The cost of electricity in Massachusetts was obtained from the U.S. Energy Information Administration (US EIA, 2010) and the inflation rate was set according to data from the Bureau of Labor Statistics (BLS, 2010). Information on the incentives available for wind projects were attained through several interviews with several individuals at the DOER who had knowledge of state and federal incentives as well as from the “Database of State Incentives for Renewables and Efficiency” (DSIRE, 2009). Even with this information, we still had to make some assumptions, which are listed below and can be found in Appendix E.

- Custom equation for calculating power
- Installation is 80% of the cost of the turbine
- Turbine produces 0.20% less energy each year
- Electricity costs 16¢/kWh

- Yearly maintenance is \$100: We assumed a yearly cost of maintenance and loss in energy produced based on interviews with wind turbine manufacturers and installers.
- Inflation is fixed at 2%
- RECs are fixed at \$30/REC
- Arrays of turbines only add a small installation discount (depending on the size of the array)

We assumed a value for the cost of installation at 80% of the cost of the turbine based on interviews with wind turbine installers and manufacturers, as well as an interview with a structural engineer. We had to assume a value because the installation cost depends on the effort required to get the turbine on top of the building as well as constructing a proper mounting system that must be integrated into that building. We also assumed a yearly cost of maintenance and loss in energy produced based off of interviews with wind turbine manufacturers and installers. A very small value was used for loss in energy production because while yearly maintenance should theoretically keep the turbine working at peak efficiency, interviews with various wind turbine owners reveals that this is not always true, so we decided it would be more accurate to assume a very small loss in production. Another major assumption is that with multiple turbines there is only a small discount on the installation cost of each turbine, based on how large the array is. This assumption was based off very limited information from installers, as we found no studies discussing the economic benefits of arrays and so our calculation methods for arrays may not accurately reflect the cost of an actual array installation. As mentioned in Section 3.2 we calculated the power each turbine would produce. The equation used for this is explained in Section 4.2. Lastly, we assumed fixed values for the cost of electricity, inflation, and the cost at which renewable energy credits can be sold, which is simply unrealistic. However, it is very difficult to predict the changes in these values over time and this was out of the scope of our project.

It is not enough to simply know the payback period of a wind turbine, but also what the acceptable payback period is for the people who may be installing them. Of course any wind turbine that has a payback period beyond its expected lifetime should not be considered, as it will never make enough money to justify its purchase. However, for the wind turbines that pay for themselves within their lifetime, we needed to know if their payback period was short enough to be considered for use on buildings. To accomplish this, we interviewed managers from real estate corporations including Hines, Massachusetts Convention Center Authorities and Boston Housing Authorities to find a range of acceptable payback periods, keeping in mind that wind turbines are a renewable source of energy and might have benefits beyond pure energy production. The only problem with these interviews was that they gave only the viewpoints of corporate building owners, and not any individual building owners, although corporations are more likely to have the initial capital required for such an expensive endeavor as a wind turbine.

### **3.4 Social Concerns and Motivations to Rooftop Wind Turbine Installations**

Public support or opposition to any project is important because it has an impact on a project's approval and success. Therefore, we focused on determining any problems that current rooftop wind turbine installations in Boston have encountered. We also explored what would

motivate building owners to install rooftop wind turbines. In order to accomplish this, we based our research on the following important questions:

- What sorts of building owners might be inclined towards rooftop wind turbine installations?
- What reasons exist for installing rooftop wind turbines?
- What complaints do people have against rooftop wind turbines?

There are several social concerns of wind turbines that we identified both in our background research and our analysis of feasibility studies from other wind projects. These include:

- Aesthetics,
- Shadow flicker,
- Noise, and
- Disruption of wildlife.

Different areas and buildings in a city have different social factors specific to them. For example, aesthetic and noise concerns may not be as problematic in an industrial area as in a residential neighborhood. Nearby residents may be concerned with the sights or noise created by a wind turbine. Some may also think about how wind turbines could affect the surrounding bird population. To ascertain these site specific social concerns, we asked the project managers mentioned in Section 3.1 what reactions they received from people concerning the rooftop wind turbine installations.

Building owners are crucial in a rooftop wind turbine project's implementation. Any information and views that they may have about rooftop wind turbines affects their acceptance towards turbine installations. They may also have reasons besides energy production to install wind turbines such as publicity or education. As mentioned in Section 3.3 we interviewed three real estate corporations. This allowed us to draw conclusions on reasons for installing wind turbines as well as the types of building owners that may be more or less inclined to install rooftop wind turbines for varying reasons.

### **3.5 Integrative Analysis**

After every objective had been explored, we brought together the results of each into an integrated analysis of the feasibility of urban rooftop wind turbines in Boston. In order to determine the essential criteria for rooftop wind turbines, we addressed the following research questions:

- What are the most promising types of locations for rooftop wind turbines, taking into account the available technology, economics, and siting constraints?
- What social barriers may hinder rooftop wind turbines either currently or in the future?
- What factors make rooftop wind turbines more feasible either currently or in the future?
- What information is unknown about rooftop wind turbines, and of these, which would be most beneficial?



By bringing all factors together, we were able to determine which types of locations in Boston are most desirable for rooftop wind turbines based on wind speeds, building types, and electrical networks and loads. With the results of this analysis, we were able to come to an overall conclusion of what conditions need to be met in order for rooftop wind turbines to be feasible in Boston. By considering possible changes in the future, we were able to compare and contrast how feasible wind turbines are now and how this feasibility would be altered in the future if certain factors change. This can allow the DOER to take the next steps leading to their objective of using wind power as an alternative energy source in Boston, and working towards the ultimate goal of reducing fossil fuel based energy use.

## 4 Feasibility Findings

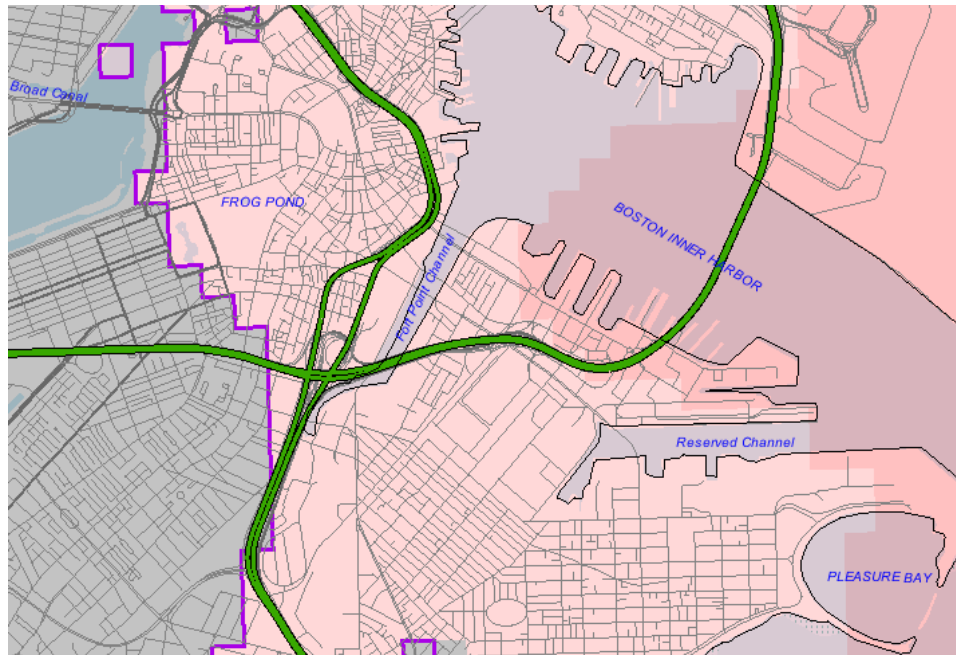
In this chapter we present the findings for our feasibility study of rooftop wind turbines in Boston. The general conclusion of our research was that rooftop wind turbines are not currently a viable source of power production in Boston, but changes in the future could have a significant impact on their feasibility. We begin with a siting study and argue that the largest problems are turbulent wind flow and NSTAR restrictions. We then provide a list of the turbines, which we believe are most suitable for rooftop installations in Boston. We also present an economic analysis which indicates that the payback periods for nominal cases are 14 to 48 years, which is not favorable, but that more favorable results can be envisioned for the future. Finally, we present views from real estate firms, project managers of existing rooftop wind turbines in Boston, urban wind turbine studies, and small wind turbine manufacturers on the social concerns and motivations regarding rooftop wind turbine installations.

### 4.1 Site Study of Boston

This section focuses on the major aspects that determine how suitable a specific site is for rooftop wind turbines: wind resources, zoning regulations, roof structure, and grid connection. Boston, being a coastal city, has sufficient wind speeds, but the density and variety of structures has a negative effect on the wind quality. Zoning laws restrict the size and noise of wind turbine installations. Also, the roof support needs to be strong enough to handle the static and dynamic loading caused by the operation of wind turbines. Interconnection to the electrical grid is another important challenge, especially in an urban area with complex networks that require special care to allow distributed generation.

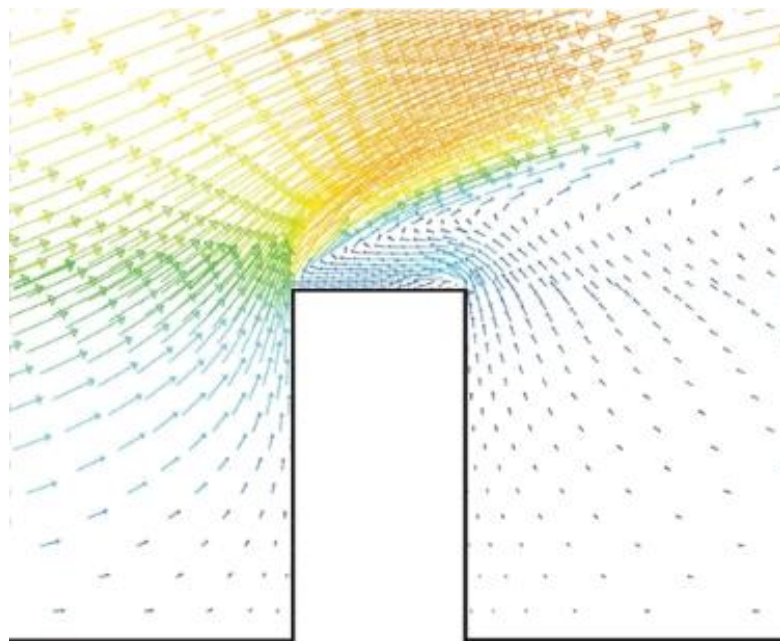
#### 4.1.1 Wind Characteristics in Boston

Adequate wind resources exist in Boston, but obstructions cause turbulent wind conditions, which can be avoided with increased elevation and proper siting. Based on the National Climatic Data Center the average annual wind speed for Boston at an elevation of 30 meters (98 feet) is 5.54 m/s (12.4 mph) (NCDC, 2008). This meets the average wind speeds of 5.5 m/s (12.3 mph) or higher, which is recommended for wind turbines by Mithraratne (2009) and Cace et al. (2007). It should be kept in mind that this is only an average and varies with location, such as at the Museum of Science, where the Boreal Renewable Energy Development estimated an average wind speed of 5.09 m/s (11.4 mph) at 43 meters (141 feet) (Gross, Phelan, & AeroVironment, 2006). It should also be noted that wind speeds increase as elevation rises and there are several equations that can be used to calculate this increase, a few of which can be seen in Appendix D. While averages are helpful, maps that show location-specific wind speeds provide data that is more useful for siting, such as the map in Figure 5 from the Geographic Information Survey, showing wind speeds in Boston at an elevation of 70 meters (230 feet) (MA GIS, 2007). The darker pink area to the right represents wind speeds of 6.5 to 7 m/s (14.5 to 15.7 mph), while the lighter pink area represents wind speeds of 6 to 6.5 m/s (13.4 to 14.5 mph). The purple outlines represent boundaries between higher wind speed area in pink and very low wind speed area in grey.



*Figure 5 - Boston Annual Wind Speeds at 70 meters (used with permission from MA GIS, 2007)*

To fully understand the wind resources available in Boston, the effect buildings have on the wind flow must be assessed. Figure 6 shows how wind is affected while flowing over a building. The arrows represent the wind coming from the left side; long and bright arrows represent faster and more consistent laminar winds, while short and dark arrows represent slower and more irregular turbulent winds.



*Figure 6 - Wind flow over a building (used with permission from Mertens & de Vries, 2008)*

The wind directly on the top of a building is weak and turbulent, but higher up the wind speed becomes stronger and laminar. In fact, this wind can be 20% faster than the wind in an open space in front of the building due to the compression of winds coming from several directions above the rooftop, equating to a 70% increase in potential energy (Mertens & de Vries, 2008). A rule of thumb also suggested by Mertens and de Vries (2008) states that the hub height of a wind turbine placed in the middle of a building's roof should be approximately half the width of the roof to capture this faster wind. In addition to this, several feasibility studies suggest that it is best to place the turbine away from obstructions upwind that are higher than the surface that the wind turbine is mounted on, such as other buildings. Although the exact distance is not widely agreed upon, conservative estimates state the distance from the obstruction should be about twenty times the height of the obstruction (Dutton et al., 2005). For example, a turbine on a 100 foot building would need to be 200 feet away from a 110 foot building that is upwind.

*Wake effect*, the effect one wind turbine has on the wind supplying another turbine behind it, can be a significant challenge in creating arrays of wind turbines. When several wind turbines are installed in an array, they should be placed beside one another facing the prevailing wind direction, with at least three blade diameters in between each other. If one wind turbine must be placed directly behind another wind turbine, it should be at least five to nine blade diameters behind the front turbine, and even then there is about a 5% loss in efficiency for the rear turbine (DWIA, 2003). These requirements limit the number of wind turbines that can reasonably fit onto a roof, due to the limited area on a rooftop.

Another issue, and perhaps the most important, is the *capacity factor* of a wind turbine at a given site. The capacity factor is the ratio of the actual power output in a real-world environment to the power output specified by the manufacturer. After examining reports and production from existing rooftop wind turbine sites in Boston, we found that their capacity factor was close to the 5% average urban capacity factor suggested in several of the studies by Syngellakis, Robinson, & Carroll (2006) and Mithraratne (2009). The capacity factors for some of the wind turbine installations in Boston are as follows:

- Harvard Soldiers Field Parking Garage: 6.2%
- MOS Skystream: 9.55%
- MOS Proven: 4.91%
- MOS Windspire: 1.66%
- MOS Swift: 0.66%
- MOS AeroVironment: 0.49%

It should be noted that the AeroVironment and Swift turbines at the MOS have been determined to be either faulty or sited poorly, so they are experiencing peculiarly low capacity factors. This also demonstrates that poor siting can severely impact a wind turbine's performance. Even though these seem to suggest a low overall capacity factor, a study in the UK by Syngellakis, Robinson, and Carroll (2006) has recorded capacity factors of up to 13.6%, indicating that better siting can result in superior performance. While the difference in capacity factor is discussed in the studies, the possible differences in siting that could have caused it are often not. It is clear that siting has the largest effect on the capacity factor of urban wind turbines, but a lack of information makes urban siting difficult and suggests that more research needs to be done in the area. With improved guidelines for siting wind turbines in urban areas, it may be possible to

increase the capacity factor to 15% or even higher, especially given the fact that many of the urban wind turbines in studies do not follow the siting guidelines we have determined.

#### 4.1.2 Regulations and Zoning Laws in Boston

The zoning regulations in Boston have a relatively large impact on the installation process of wind turbines. These laws mainly affect the height and noise levels produced by a rooftop wind turbine in operation. They also list the areas in which rooftop wind turbines are allowed as well as other areas that have a conditional pre-approval.

The specific laws regarding rooftop wind turbines in the Boston area are found in Article 88 of the *Boston Zoning Code and Enabling Act* (BRA, 2009). As mentioned in Section 4.1.1, the height at which a rooftop wind turbine is placed can significantly impact the capability of the rooftop wind turbine. Regarding height, zoning laws within Boston places a height restriction on rooftop wind turbines of “forty-five (45) feet or twenty-five percent of the height of the building” (BRA, 2009). These height restrictions don’t result in a considerable reduction in wind turbine performance since the height restrictions allow the wind turbine hub to utilize the favorable wind zones above the rooftop of most buildings. Federal Aviation Administration (FAA) regulations require “that a Notice of Proposed Construction be filed for any object that would extend more than 200 feet above ground level” (MTC, p. 1, 2007). This will likely include many wind turbines on buildings, which means that most potential installations will be subject to an aeronautical study by the FAA. The Massachusetts Technology Collaborative (MTC) describes this process as “daunting and highly complex” and suggests one “enlist the services of professional aviation consultants, and bring them into the process early in order to advise on the technicalities of FAA regulations” (MTC, pg. 4, 2007). While this raises another potential cost, the MTC states it is approximately \$500, which is not significant considering the installations cost several thousands.

Zoning regulations also restrict the noise created by a rooftop wind turbine, depending on the location it is placed in. The specific noise limits for different areas can be seen in Table 4. Based on these limits, the loudest noise a rooftop wind turbine would be able to produce is 50dB in order to be considered for all parts of the city. However, a wind turbine can have a noise limit of 55dB if installed in a mixed-use residential/ industrial area or 65dB if installed in a business district. This only removes a few small wind turbines from consideration, as most small turbines produce less than 55dB of noise at their rated wind speed.

Districts	Residential		Residential/Industrial		Business	Industrial
Time of Day	Daytime	Other Times	Daytime	Other Times	Anytime	Anytime
Sound Limit (dB)	60	50	65	55	65	70

*Table 4 - Noise regulations in Boston*

Prior to installing a rooftop wind turbine an installer or owner must take some additional steps to insure that he/she abides with the zoning laws. One such example is, “the applicant shall provide a copy of the project summary, electrical schematic, and site plan to the Boston Fire Department.” These additional considerations also take into account the impact of the turbine on nearby property, as indicated by the provision “wind energy facilities shall be sited in a manner that minimizes shadowing or flicker impacts.” While these additional considerations are an

important part of the siting process, they are too numerous to list here, and the reader should consult Article 88 for further information.

Lastly, the zoning laws state several districts in Boston that specifically allow rooftop wind turbines:

- General Industrial
- Maritime Economy Reserve
- Waterfront Industrial
- Waterfront Manufacturing

They also specify districts, which have a conditional pre-approval and thus require extra documentation in order to get a final installation approval. This list can be found in Appendix F. It should be noted that wind turbines could be placed on any building with a height of over 300ft in all districts in Boston, as long as the turbine is rated at or below 6kW (BRA, 2009)

### 4.1.3 Structural Integrity of Roofs

For a building to fully support the static weight of rooftop wind turbines, the turbine pole should be secured to the column supports of a building. After consulting a structural engineer from Parsons Brinckerhoff, we found that these column supports can easily support loads up to 10,000 lbs, which is not exceeded by any turbine rated from 5 to 50kW. However, some roofs are not supported with columns, such as that of Boston Convention Center, which is supported by trusses. It is difficult to secure the wind turbines to roofs that have trusses, due to the fact that trusses often cannot sustain the same weight loads as roofs supported with columns. Therefore, these types of roofs should only be considered for lightweight rooftop wind turbines. However, columns support most high-rise buildings and buildings over four stories, which include most of the buildings within the center of Boston.

There are a few obstacles that can make mounting rooftop wind turbines a challenge. For some buildings, the *overturn force* can be too severe to keep the rooftop wind turbines from falling over. This overturn force is caused by wind hitting the wind turbine, which creates a bending motion along the pole. Thus, guy wires should be used to secure the wind turbines to the roof; these wires are cheaper than a self-supported pole, but take up more space. Guy wires help counteract the overturn force, and also require less support at the base of the turbine pole when compared to self-supported poles.

Vibration can be another challenge with rooftop wind turbine installations. The wind turbines need to be directly connected to the main frame of the structural support of the roof in order for it to be completely secured and to minimize the risk of the turbine falling over. It is required that the turbine pole penetrate 20-60 cm below the roof and have rubber buffers or other types of vibration insulation to ensure that the vibration caused by the turbine's operation does not compromise the structure of the building it is on (Shaw et al., 2009).

Historical buildings present another type of challenge for mounting rooftop wind turbines. According to the Boston Landmarks Commission, which preserves historic sites throughout Boston, there are a few things that need to be done prior to installing a wind turbine to the roof of a historical building. If a proposed building is over than 50 years old, then a permit from the Boston Landmarks Commission is required. The site must meet the following criteria in order to be granted this permit:

- The rooftop wind turbine must be visually compatible with the historical property
- The wind turbine should not damage the roof via vibration or weight
- It should be possible to remove the turbine without leaving any former presence on the roof.

#### 4.1.4 Grid Interconnectivity

The supplier of Boston's electrical energy, NSTAR, has numerous restrictions regarding the interconnection of *distributed generation* (DG) sources, presenting challenges for rooftop wind turbines to be connected to the electrical grid. The three types of electrical networks in Boston are radial, area, and spot networks, as explained in Section 2.5.4. Radial networks are common in suburban and rural areas and present very few challenges when connecting a DG source. Therefore, we saw no need to address connection to radial networks, as this is straightforward with few restrictions. Area networks are used in many urban areas and present nearly insurmountable challenges for DG. Because of these complications, there is currently no way to connect a wind turbine to an area network – an attribute of these types of networks that NSTAR would have to address. This leaves spot networks, which are found among area networks in urban environments, often connected to high-rise buildings, hospitals, and in general, most buildings above four stories in height. Spot networks present more challenges than radial networks, but can still be connected to, unlike area networks.

The main challenge for spot networks is that NSTAR will typically not allow a DG source to produce more than 1/15<sup>th</sup> of the building's minimum load. This limit is set in place to provide a safety factor to ensure that network protectors remain closed. The main concern for NSTAR is providing reliable and safe energy, because as an electric utility provider, they have an obligation to provide dependable service to their customers. Network protectors can be activated with 1-2 kW of reverse power, potentially leading to a power outage in the building and unsafe conditions for utility workers.

Despite this low allowance, 1/15<sup>th</sup> of a typical office building's electrical load is a sizeable amount to be generated due to the extremely high loads of these buildings. However, in times of low electricity consumption such as late at night or on weekends, the 1/15<sup>th</sup> limit could become a problem. On top of this, the load demand can be measured in 15-minute intervals. The fluctuation in power produced at different time intervals can further compound the 1/15<sup>th</sup> limit.

Additionally, NSTAR requires that any DG source must be connected to an IEEE and UL certified inverter prior to being connected to the grid. This is also done to prevent unreliable and unsafe conditions within the network. Since most manufacturers provide an inverter with their model, the only concern is to make sure the supplied inverter is IEEE and UL certified.

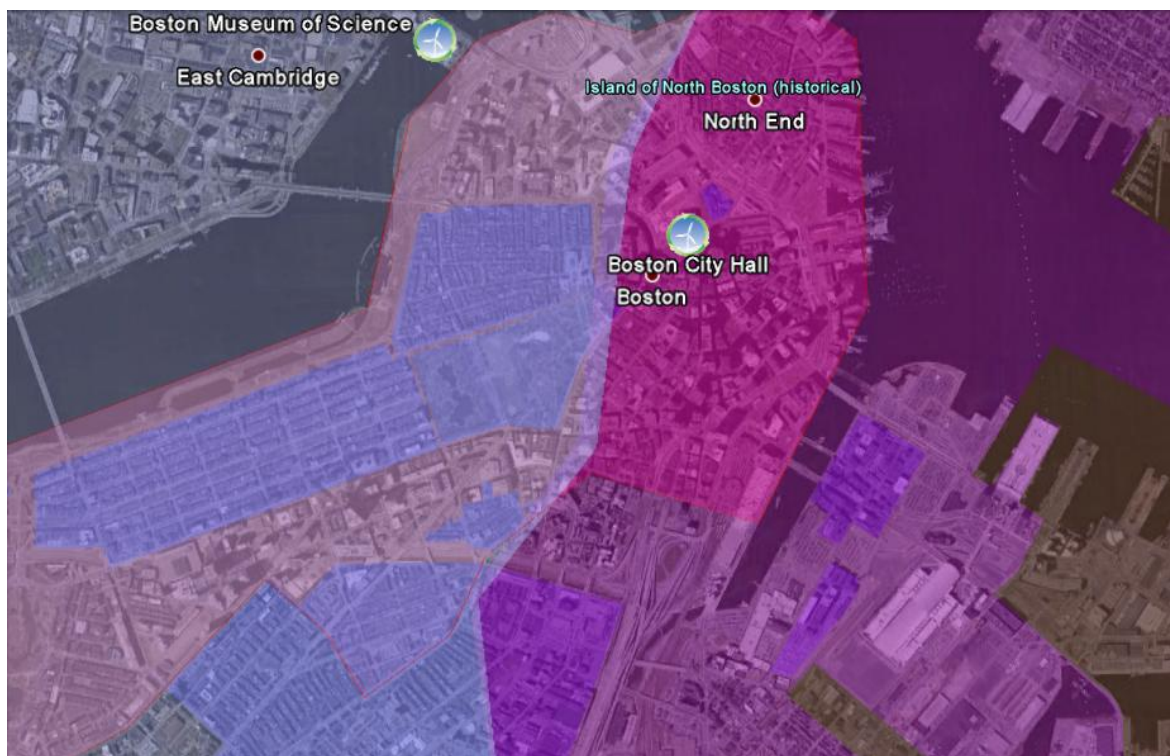
Utility companies across the country have looser regulations on DG and several allow DG to produce 30% to 50% of the building's minimum annual load (NSTAR, 2010). Currently NSTAR, IEEE and other stakeholders are in the process of changing the restrictions on DG. This could potentially lead to a higher limit on the power production of DG in Boston. NSTAR believes these restrictions will be finalized sometime within 2010.

### 4.1.5 Integrative Siting Map

Wind turbine siting conditions vary throughout Boston, so to aid us in determining suitable sites, we developed an interactive map using Google Earth that contains layers with information on different siting aspects including:

- Wind speeds at 70 meters,
- Electrical networks,
- Historical areas,
- Approved zoning districts, and
- Avian active areas.

Figure 7 shows a map with all the overlapping layers. This map can be useful to determine if a specific site is favorable for wind turbines. By considering each layer, which represents a different siting factor of rooftop wind turbines, it is possible to determine what is good about a site and what needs consideration.



*Figure 7 - Integrative Map of Boston Siting Factors*

In Figure 7, the dark purple area to the right indicates higher average wind speeds than the lighter area to the left, due to its proximity to the ocean. These wind speeds can indicate sites with particularly good wind resources that are more favorable for wind turbines. The red shaded area is where area networks are located. There are many spot networks within this region, but due to security reasons, NSTAR was unable to provide us with their specific locations; these can be explored on a case-by-case basis. The avian habitats were located with maps provided by the



Massachusetts Audubon Society and show areas where wind turbines might disrupt local wildlife. However, none of these areas are present in the figure. The blue shaded regions picture historical areas, and zoning districts approved by Article 88 are the dark brown regions along the waterfront. This information was found with the help of the Boston Landmarks Commission and marks areas that are subject to stricter restrictions on such sites, as discussed in Section 4.1.3. Individual layers of the map can be seen in Appendix B.

## 4.2 Comparison of Rooftop Wind Turbine Models

In this section we explain how we determined a list of promising turbine models based on a comparison of their characteristics. We also explain how we used a performance analysis tool to come up with the list of promising turbine models within three distinct divisions.

Theoretically, vertical axis wind turbines (VAWTs) are more suited for turbulent areas, but in practice current models of horizontal axis wind turbines (HAWTs) tend to be more efficient. During our interview with the project managers at the Boston Museum of Science they provided data of the different rooftop wind turbines they have installed. Based on the data the Skystream wind turbine, a HAWT, proved to be most efficient, while the Windspire wind turbine, a VAWT, performed poorly. Both turbines were installed on the same roof, although the difference might be due to siting. We also talked to an associate from the CADMUS group, who confirmed that VAWTs do not currently perform better than HAWTs on roofs even in a turbulent environment. This warrants more research and development into the efficiency of VAWTs in urban environments, since it appears their actual performance doesn't currently hold up to their theoretical performance.

We examined the small wind turbines currently available and classified which types would be best suited in the urban environment of Boston. We compiled data from multiple online databases and listings to obtain a listing of about 480 small wind turbines, of which 400 were HAWTs and 80 were VAWTs. We understand that there are more turbines available; however, we concentrated on the models, whose information was readily available online. The major manufactures of small wind turbines existed in the Netherlands, the United Kingdom, the United States, Canada, and China. These countries each had about five to ten manufacturers; other countries also produced turbines, but tended to only have one manufacturer. It was important to note the country in which the turbines were manufactured, since shipping could add a significant cost to the initial cost. We also observed that the manufacturers in the Netherlands and the United Kingdom have been in the industry for the longest time and have had more time to perfect their designs. For example Proven Energy, which is based in the United Kingdom, has been in the industry for almost 30 years. Proven has utilized this time to improve all aspects of their designs, such as their blades on HAWTs, which have hinges that allow for better performance in turbulent and high wind conditions.

Since there are many variations in the designs of rooftop wind turbines, we decided to separate the overall list into three distinct divisions:

- VAWT
- HAWT with a diameter between 7-25 feet
- HAWT with a diameter between 26-50 feet

These divisions were formed due to the fundamental differences between VAWTs and HAWTs as well as the difference in performance of HAWTs with varying blade diameters. This division also provides a variation of designs that may suit different sites. Following this division we created criteria to reduce the turbine model list to provide models best suited for Boston. The criteria we used are as follows:

- Blade diameter: under 50 feet (only for HAWTs)
- Power rating: 5-50 kW
- Cut in speed: at or below 7 mph (3.1 m/s)
- Weight: at or under 10,000 pounds
- Noise: at or below 55 dB

We chose the above criteria to allow for an array to be installed since it takes the available space limitations, zoning requirements, wind conditions and weight restrictions into consideration. The square of the radius of HAWTs is proportional to the amount of energy they can capture from the wind. However, blade diameter shouldn't get so large such that it wouldn't allow the turbine to fit on the rooftop or cause wake effect. This aspect of wind turbine design was important in guiding us to choose the appropriate blade diameters which would allow for maximum power production on the limited roof area.

As mentioned in Section 4.1.3 wind turbines weighing 10,000 lbs or less will not damage a typical roof of a high-rise building. The DOER is interested in offsetting the energy loads of buildings in Boston, and since high-rise buildings have loads of several thousand megawatts, a wind turbines rate for 5-50kW could provide this offset if placed in an array. We did not add height to the criteria, since installers will install any height that the building owner asks for, provided it is reasonable. Since the average wind speed in Boston is 5.54 m/s (12mph), we chose 3.1 m/s (7 mph) as a limitation for cut-in wind speeds.

From these criteria we were able to reduce the list to 93 turbine models; 15 of these models were VAWTs and the rest were HAWTs. This list is provided in Appendix C. The rated power and cut in speed ended up being the criteria that eliminated most of the models. The noise and blade diameter only eliminated about four models each. The weight criteria did not eliminate any of the models. Another major reason that models were eliminated was due to missing information and discontinued models. Additionally, some manufacturers did not provide adequate information for us to use them in our comparison. We attempted to call these manufacturers; however, many were not reachable or there was no contact information on their websites. If we could not find the cut-in speed or the blade diameter of a wind turbine model, it was eliminated. We made sure to keep all the discarded models to inform future studies.

To show the performance of a specific wind turbine manufacturers provide a power rating as well as a power curve for each model. The power rating represents the power the wind turbine produces at the nominal wind speed or the production wind speed. The power curve shows the various power outputs that are obtained at different wind speeds. We originally thought we would use the power curves of different models and compare the power production of each based on the average wind speed in Boston. However, during our research and interviews with the Boston project managers in Boston, we discovered that the power ratings and power curves do not always match the performance characteristics reached in testing. This can be seen in Figure 8, which is from the Warwick trials in the United Kingdom (Warwick, 2009). The red line represents the manufacturer's power curve, and the blue dots represent wind speed and power

measurements taken at 10-minute intervals over approximately 270 days. Although the tested values almost agree with the power curve at lower wind speeds, at higher wind speeds this is not the case. In fact the turbine is rated at 600W, but the power only reaches about 300W. The MOS data also showed that the actual performance results for some of the wind turbines varied from the actual power curves. A few of their installed turbines matched the power curves almost exactly, but many didn't. Due to the inconsistency of the data provided by the manufacturer and real-world data, we decided to seek an alternative means to compare the power performance of the various models.

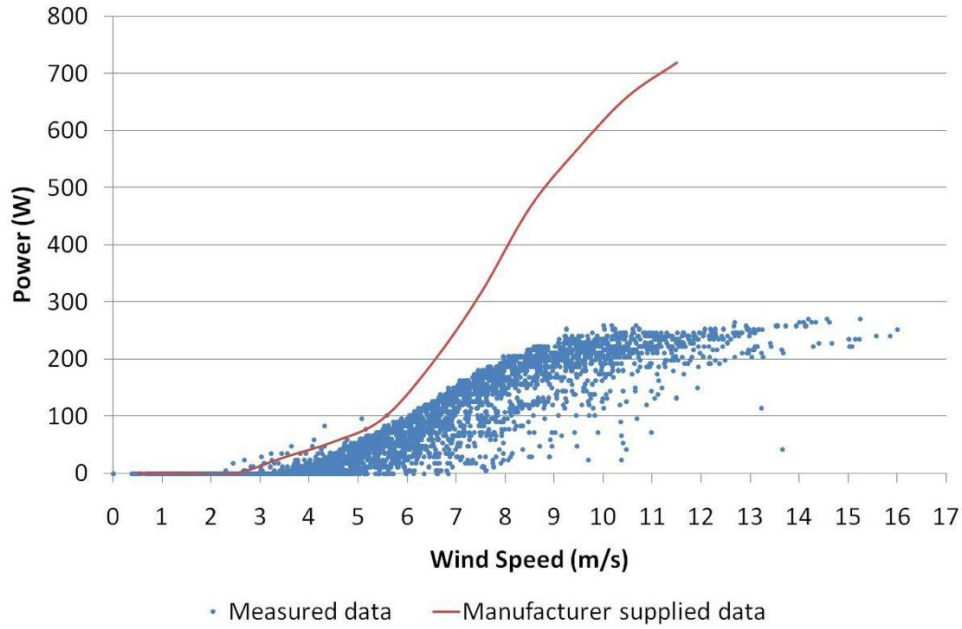


Figure 8 - Warwick wind trial power curve (used with permission from Warwick Wind Trials, 2009)

To compare the performance of the remaining 93 turbine models we estimated the power produced by each model using the power equations. For HAWT models we used the following equation and incorporated the capacity factor to it (Menet et al., 2000):

$$P = \frac{1}{2} \rho_{air} C_p(\lambda, \theta) \pi r^2 v_w^3 (CF)$$

where

$r$	is the wind turbine rotor radius,
$v_w$	is the wind speed,
$\rho_{air}$	is the mass density of air,
$C_p(\lambda, \theta)$	is the aerodynamic efficiency, a function of the blade, pitch angle $\theta$ , and tip speed ratio $\lambda$ ,
$CF$	is the capacity factor, the actual power output over the rated power

Using our wind speed calculator, which is presented in Appendix D, we were able to estimate an average wind speed at 145 meters, by using the average speed of 5.5 m/s at 70 meters from the

study conducted by Boreal for the Museum of Science. We found that the wind speed at 145 meters is approximately 8.5 m/s. We added 20% to this, the percentage that is gained from proper siting on a roof, and got 10.2 m/s for our calculations. The air density at sea level is 1.23 kg/m<sup>2</sup> and the power coefficient can reach a max of 0.593, known as the Betz Limit, so we assumed these values for our calculations. We also assumed a capacity factor of 15% for HAWTs with adequate siting in an urban environment.

Assuming the power coefficient at a fixed rate for all the turbines is a cause for error, since power coefficient varies for different airfoils. Another reason this calculation is not completely accurate is because it does not take into consideration the efficiency of the generator, gearbox/bearings, or power electronics of the different wind turbine models. This could be a problem, since the only variable that changes when using this equation is the swept area of each model, which is a function of the diameter.

We were able to find power equations for VAWTs, including one for Darrieus models and one for Savonius models (Menet et al., 2000). However, we were unable to find the equations for all the different VAWT designs, such as H-rotor, and we did not have numbers for the different variables. Therefore, we compared the VAWT models based on the power ratings.

To determine promising turbine models in each of the three categories we used a spreadsheet to sort the turbines by power produced (or rating for VAWTs), then by cut-in speed, and finally by production speed within each division. From this we chose the top five models within each division, which are shown in Table 5.

Type	Manufacturer	Rated Power (kW)	Annual Power Production (kWh)	Cut-in Speed (mph)	Production Speed (mph)	Diameter (ft)
VAWT	Venco Power GmbH	50	N/A	5.6	26.8	39.37
	Windports	20	N/A	5.6	32.44	14.44
	Ropatec AG	20	N/A	6.7	N/A	26.25
	WePower	12	N/A	6	29	20
	UrbanGreenEnergy	10	N/A	4	12	N/A
HAWT (7-25)	A&C Green Energy	10	5,562	6.7	24.6	25
	Altem Power	10	5,386	5.6	24.6	24.6
	Aeolos Wind Energy	10	5,386	6.7	22.3	24.6
	Abundant Renewable Energy	10	4,957	6	23	23.6
	Century Wind Energy	12	4,753	4	22.4	23
HAWT (26-50)	Hannevind	30	15,454	4.4	20	42.7
	Hannevind	22	15,454	4.4	20	42.7
	Nanjing Supermnn Industrial	50	15,454	6.7	26.8	42.7
	Aventa Ltd	6.5	14,443	4.47	13.4	41.28
	Aeolos Wind Energy	30	14,248	6.7	22.3	41

*Table 5 - Top turbine candidates based on theoretical performance*

We noticed from our calculations and the above table that some models, especially in the 26-50 ft range, produced similar annual power productions despite the fact that their power ratings varied greatly. We already established that manufacturers do not always provide accurate power ratings, but we think that this does not fully explain why a 6.5kW and a 30kW rated wind turbine would have the same blade diameter and thus provide almost equivalent annual power production. This is just one of the more extreme cases, but this applies to many of the models we compared. Our calculations could be much more accurate if the manufacturers provided efficiency ratings for their airfoils, generator, gearbox/bearings, and power electronics. If these values were known, they could be incorporated into the power equation. With the revised power equation the models would likely agree more with the power ratings.

### 4.3 Economic Analysis of Rooftop Wind Turbines

Currently, the biggest barrier to introducing rooftop wind turbines to Boston is the lengthy payback period. Like any investment, wind turbines need to be economically viable. However, small wind turbines have a high cost that is not adequately offset by their low power production, unlike larger scale wind turbines. While government incentive programs offset this cost a bit, currently available rooftop wind turbines will not generate enough energy to be considered economically sound based on their cost. Despite this, there are several changes that could make wind turbines economically feasible in the future, such as more efficient turbine designs or increased cost of electricity.

To analyze the economic factors involved in installing a rooftop wind turbine, we created an economic analysis tool using Microsoft Excel that could be used in conjunction with our list of wind turbines. We did this because the economic calculators we found were either too complex/confusing or too simple to be of use to us. Additionally, creating our own calculator allowed us to integrate it into our database of small wind turbines. This calculator takes into account all the major factors, including the cost of the turbine, installation, maintenance, and loss in turbine productivity, all of which can be seen in Figure 9. The beige cells require input from the user, while the green inputs are automatically taken from the turbine list. We chose the Nanjing Superman LS-10kW horizontal wind turbine for the economic analysis presented in this section because it was one of the turbines with a relatively short payback period. The attributes of the LS-10kW can also be seen in Figure 9. Each input to the economic analysis tool is discussed in further detail in Appendix E. Measured against other economic calculators, as discussed in the methodology, our calculator gave results that differed only 2-5% from the results from similar economic calculators, and so we were confident in its accuracy. However, there were some areas where assumptions were required, the most important being a capacity factor of 15%, which is achievable according to several of the studies we found. Additionally, we assumed that an array of three wind turbines was being installed because it was more economically viable. The other assumptions are outlined in Section 3.3 and in Appendix E.

Number of turbine from list:	84
Turbine name:	LS-10kW
Manufacturer name:	Nanjing Supermnn Industrial
Number of Turbines:	3
Turbine rating (kW):	10
Energy produced by turbine(s) (kWh/year):	17,366
Energy used by building (kWh/year):	4,548,318
Percentage of total energy generated by turbine (%):	0.38%
Cost of electricity (\$USD/kWh):	\$0.16
Cost of turbine and tower (\$USD):	\$10,294.00
Cost of installation (\$USD):	\$7,411.68
Yearly cost of turbine (\$USD):	\$100.00
Net metering rate (\$USD):	\$0.16
Turbine expected lifetime (years):	20
Turbine loss in productivity (%/year):	0.20%
Rate of inflation (%/year):	2.00%

Figure 9 - Factors taken into account when evaluating economic viability.

In addition to the inputs from the user, such as the turbine rating and estimated energy production, our calculator also factors in the numerous economic incentives available in Massachusetts, such as the Production Tax Credit. The list of incentives taken directly from the calculator is shown in Figure 10, with the column on the right displaying the value each particular incentive is providing the project. A detailed description of each incentive available for small wind projects can be found in Section 2.2. One major factor to note for the incentives is the “Price per Renewable Energy Credit” is subject to change as demand for Renewable Energy Credits (RECs) increases or decreases.

<b>Massachusetts Incentive Programs</b>		
<u>Renewable Portfolio Standard</u>		
Renewable Energy Credits produced (RECs/year):	25	
Price per Renewable Energy Credit (\$USD):	\$30.00	
Income from RECs per year (\$USD):	\$750.00	
<u>Production Tax Credit</u>		
Amount per kWh (\$USD/kWh):	0.021	
Years eligible (years):	2	
Total incentive per year (\$USD):	\$528.27	
<u>Federal Investment Tax Credit</u>		
Amount (\$USD):	\$24,300.00	
<u>Alternative Energy Exemption</u>		
	100% excise tax deduction	
<u>Renewable Energy Equipment Sales Tax Exemption</u>		
	100% sales tax deduction	
<u>Renewable Energy Property Tax Exemption</u>		
	100% property tax deduction for 20 years	

Figure 10 - Government incentives taken into account in economic calculator

Our calculator processes all the input and provides the user with a graph displaying the *net present value* of the investment for the lifetime of the turbine. Net present value is how much value the wind turbine has generated minus how much the wind turbine has cost up to a particular time. Additionally, the calculator also displays the net present value of an equivalent investment into a savings account with a user defined interest rate to see if the savings account might be a wiser investment than a wind turbine. This is then compiled into a graph similar to the one shown in Figure 11. The graph shows the net present value of the rooftop wind turbine in blue, alongside the net profit from the savings account investment in red, over the wind turbine’s expected lifetime. This type of comparison to a savings account is done by many corporations to examine how a potential investment matches up to simply keeping the money in a bank, although fairly high interest rates are often used, in this case 6%. The point at which the wind turbine’s net present value crosses the x-axis is the point at which the turbine has paid for itself, and therefore the time it took to reach that point is the payback period. Table 6 lists the payback period and key assumptions for this initial examination.

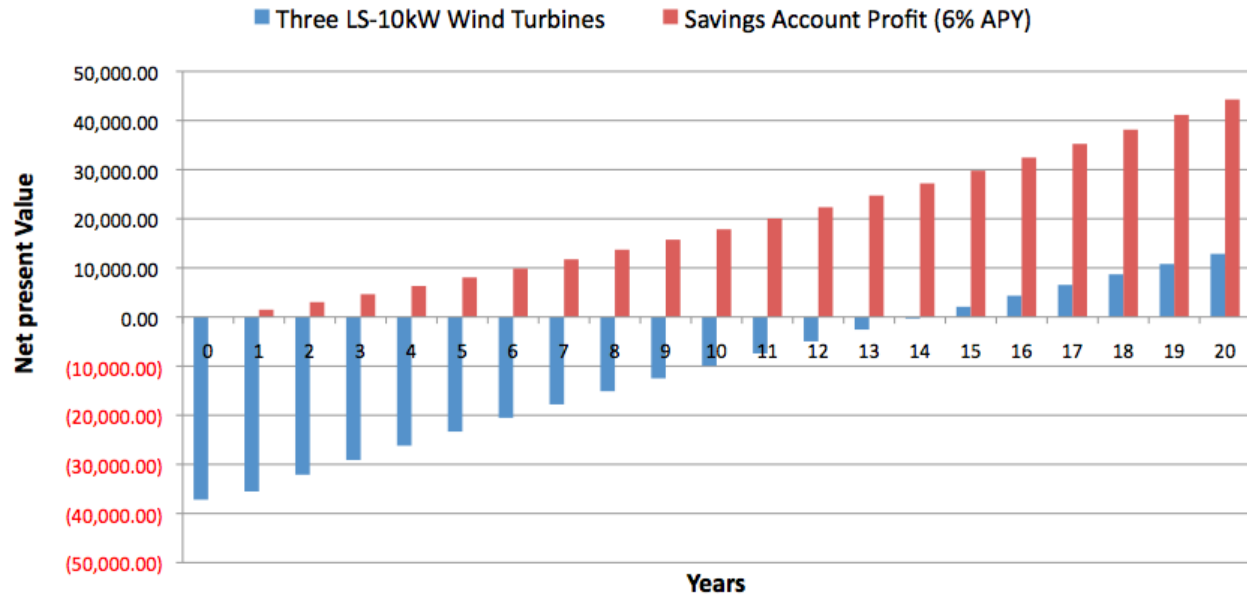


Figure 11 - Net present value of a wind turbine investment compared to a savings account investment

Capacity Factor	15%
Cost of Electricity	16¢/kWh
Cost of RECs	\$30/REC
Payback Period	14.1 years

Table 6 - Payback periods and assumptions in the calculations for Figure 11

With this calculator, we found that all of the eligible wind turbines we had in our list had payback periods ranging from 14 to 48 years. This was either beyond the expected lifetime of the wind turbine, or was simply too long for many building-owning corporations. Hines and the Boston Housing Authority, for example, are looking for investments with a maximum payback period of seven years and twelve years respectively.

Rooftop wind turbines may not be economically feasible currently, but several factors could change in the future which might have a large impact on the average payback periods. The most obvious answer is more power output, which will lead to more electricity being sold, which is the largest yearly income factor for rooftop wind turbines. The low power output of current wind turbine models is primarily due to the low capacity factor discussed in Section 4.1.1, which we use to predict how much power a wind turbine would produce in an urban environment, as discussed in Section 4.2. However, the capacity factor in some studies has been as high as 15%, and can likely increase due to exceptional siting and improvements in small wind technology, leading to enhanced performance. The effect of increased capacity factor can be seen in Figure 12, which shows the net present value of a wind turbine investment with a capacity factor of 10%, 15%, 20%, and 25%. Table 7 shows the large effect even small changes in capacity factor can have on payback period. This large increase is due to the additional sale of electricity and RECs, which are proportional to the power produced. This is below the twelve-year threshold for many building-owning corporations, and shows that even a minor increase in capacity factor can produce a significant improvement for the payback period. This increased capacity factor might also be achieved in the near future, as opposed relying on large jumps in the prices of electricity



or RECs. As discussed in Section 4.1.1, capacity factor for some sites has reached around 14% currently, and this can be further increased by research into urban siting methods and technology.

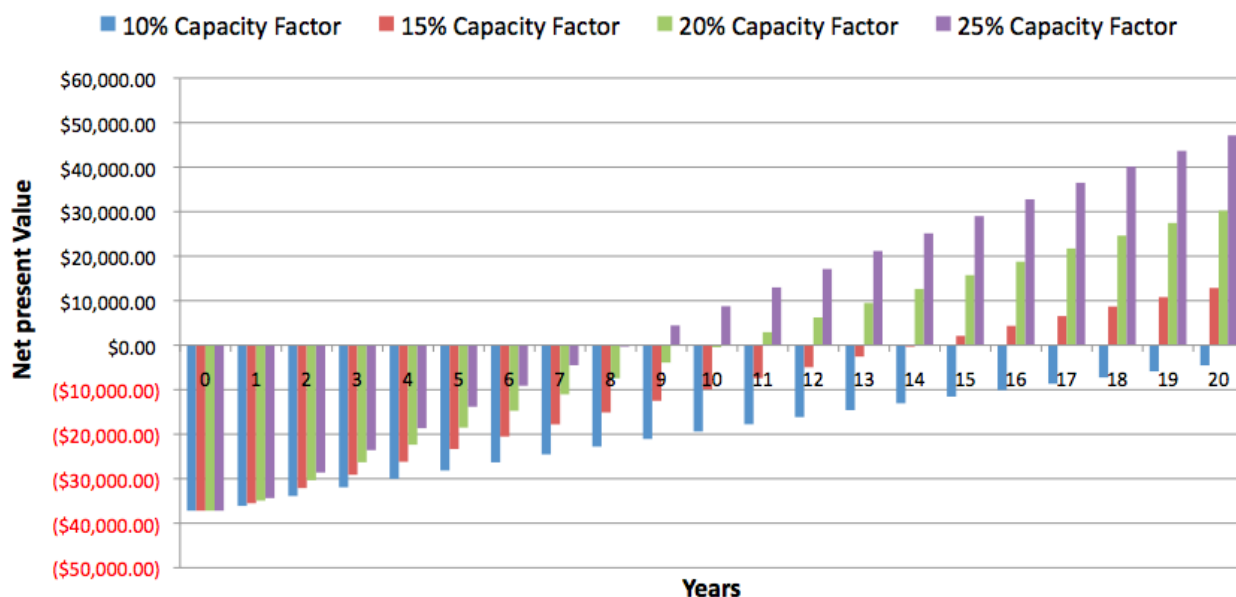


Figure 12 - Net present value given varying capacity factors

Capacity Factor	10%	15%	20%	25%
Cost of Electricity	16¢/kWh	16¢/kWh	16¢/kWh	16¢/kWh
Cost of RECs	\$30/REC	\$30/REC	\$30/REC	\$30/REC
Payback Period	23.5 years	14.1 years	10.1 years	8 years

Table 7 - Payback periods and assumptions in the calculations for Figure 12

Another possibility is that the price of electricity will increase, increasing the value of energy generated by a wind turbine. Currently, the price for electricity in Boston averages around 16 cents/kWh (US EIA, 2010). If this were to increase, the annual income generated by a wind turbine would increase as well. Figure 13 below shows the net present value for a wind turbine installation with the cost of electricity at 16¢, 18¢, 20¢, and 25¢/kWh, although the U.S. Energy Information Administration's predictions deem the latter cost very unlikely in the near future (US EIA, 2010). It can be seen in Table 8 that while the price of electricity does have a substantial impact on the economic value of a wind turbine installation, the price per kWh would have to change drastically in order for the payback period to be significantly lessened.

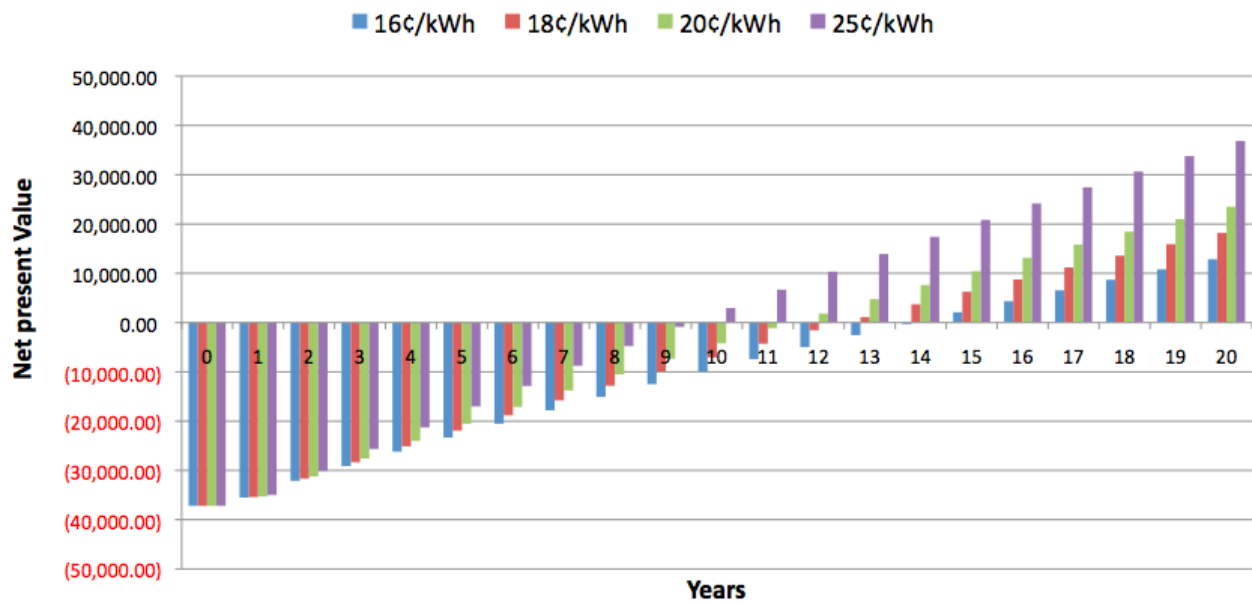


Figure 13 - Net present value with varying electricity costs

Capacity Factor	15%	15%	15%	15%
Cost of Electricity	<b>16¢/kWh</b>	<b>18¢/kWh</b>	<b>20¢/kWh</b>	<b>25¢/kWh</b>
Cost of RECs	\$30/REC	\$30/REC	\$30/REC	\$30/REC
Payback Period	14.1 years	12.6 years	11.4 years	9.2 years

Table 8 - Payback periods and assumptions in the calculations for Figure 13

Another potential change that might make wind turbines more economically feasible would be in the number or amount of government incentives offered for small wind projects. After speaking with several individuals at the DOER, we found that we could not rely on new incentives being introduced at the time this report was written, and so we examined possible increases in current incentives. Currently, one of the larger incentives is the Federal Investment Tax Credit, which is equal to 30% of the initial cost of the project. This incentive covers a sizeable portion of a wind turbine investment, but is unlikely to increase in the near future, as it was instated in 2008 and is scheduled to last until 2016. This leaves the next largest incentive, the Renewable Portfolio Standard, which sets a demand for RECs. As stated earlier, the price of RECs is based on market demand, so if demand goes up, the increased price of RECs might help make rooftop wind turbines economically feasible. Figure 14 shows the effect of increases in the price of RECs, namely at \$30, \$35, \$55, and \$70/REC. Table 9 shows that while an increase of the price of RECs can help reduce the payback period of a wind turbine project, even large increases are not enough to make such a project economically feasible. Also, as mentioned earlier, the price of RECs changes with the market, and so can change drastically over the life of a project, meaning it is probably not a stable enough base to justify a rooftop wind turbine project.

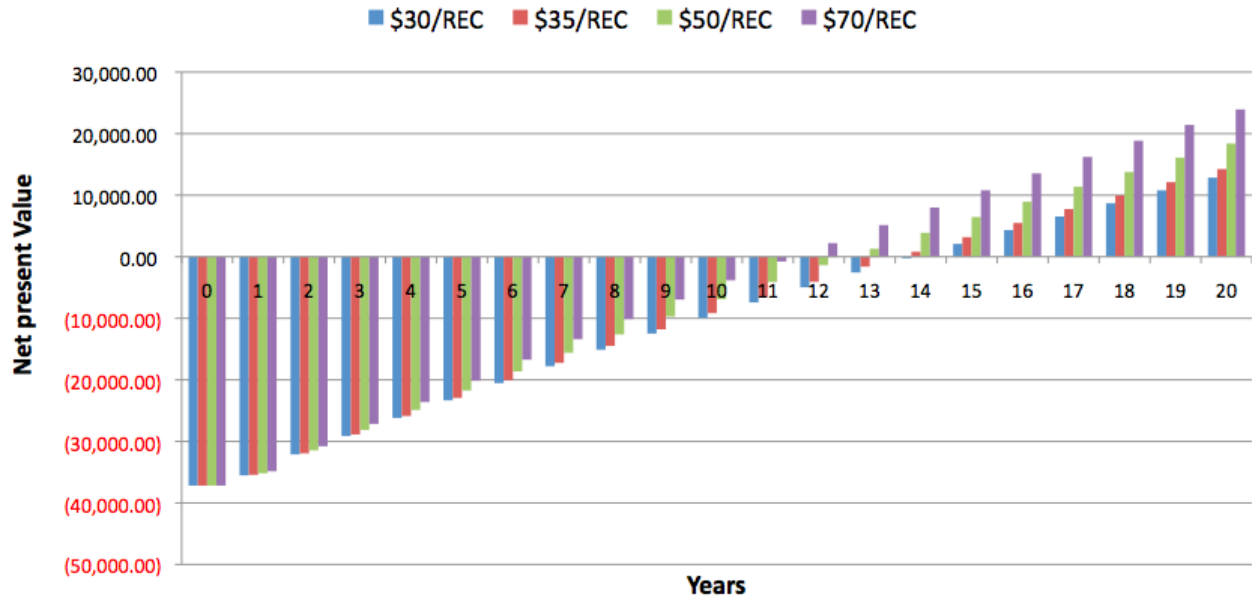


Figure 14 - Net present value given varying REC prices

Capacity Factor	15%	15%	15%	15%
Cost of Electricity	16¢/kWh	16¢/kWh	16¢/kWh	16¢/kWh
Cost of RECs	<b>\$30/REC</b>	<b>\$35/REC</b>	<b>\$50/REC</b>	<b>\$70/REC</b>
Payback Period	14.1 years	13.7 years	12.5 years	11.3 years

Table 9 - Payback periods and assumptions in the calculations for Figure 14

Out of all the factors that could result in the biggest reduction in payback period, capacity factor is clearly the largest, although a combination of all the factors discussed would have a compound effect. Figure 15 shows the effect of a modest increase in capacity factor, cost of electricity, and price of RECs. These numbers were chosen because they are small enough changes from current real-world values that they could theoretically happen in the near future. Table 10 shows that small changes in urban wind turbine capacity factor, the cost of electricity, and the price of RECs can have an overall more substantial impact on the economic feasibility of rooftop wind turbine projects than a large change in only one of those factors.

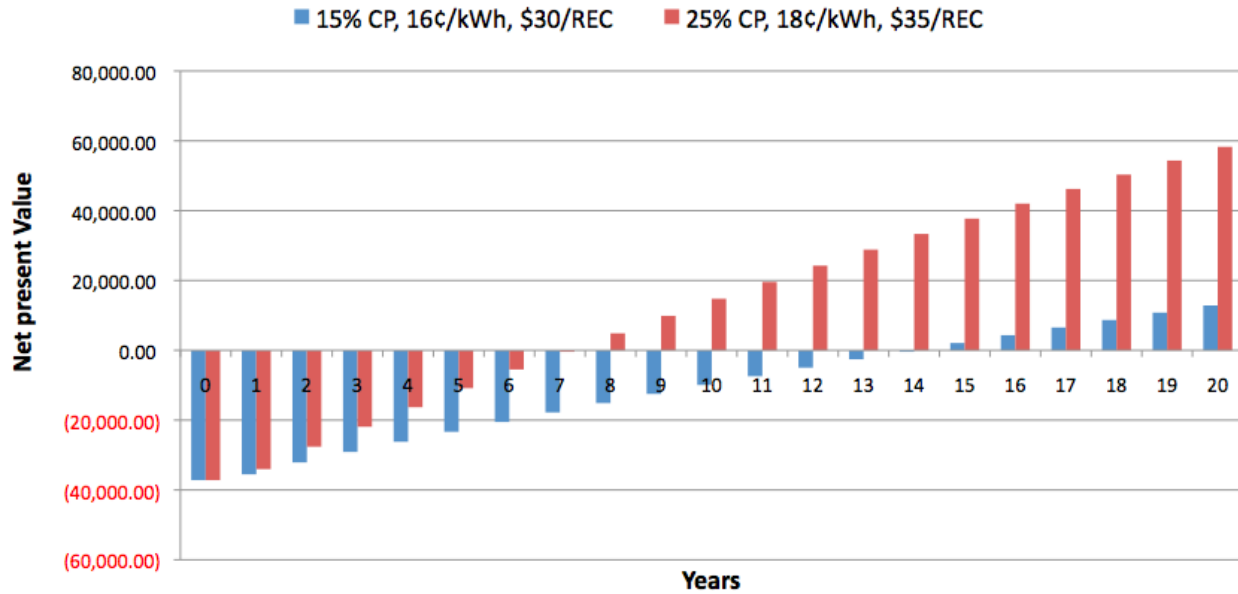


Figure 15 - Net present given an increase in capacity factor, price of electricity, and price of RECs

Capacity Factor	<b>15%</b>	<b>25%</b>
Cost of Electricity	<b>16¢/kWh</b>	<b>18¢/kWh</b>
Cost of RECs	<b>\$30/REC</b>	<b>\$35/REC</b>
Payback Period	14.1 years	7 years

Table 10 - Payback periods and assumptions in the calculations for Figure 15

## 4.4 Social Opinions Regarding Rooftop Wind Turbines

During our research, we asked project managers about the social concerns people expressed towards their rooftop wind turbines. We found that flicker was the only major social concern. Also in the process we learned that rooftop wind turbines are not installed for only power production but also for demonstration and educational purposes.

### 4.4.1 Social Concerns of Rooftop Wind Turbines in Boston

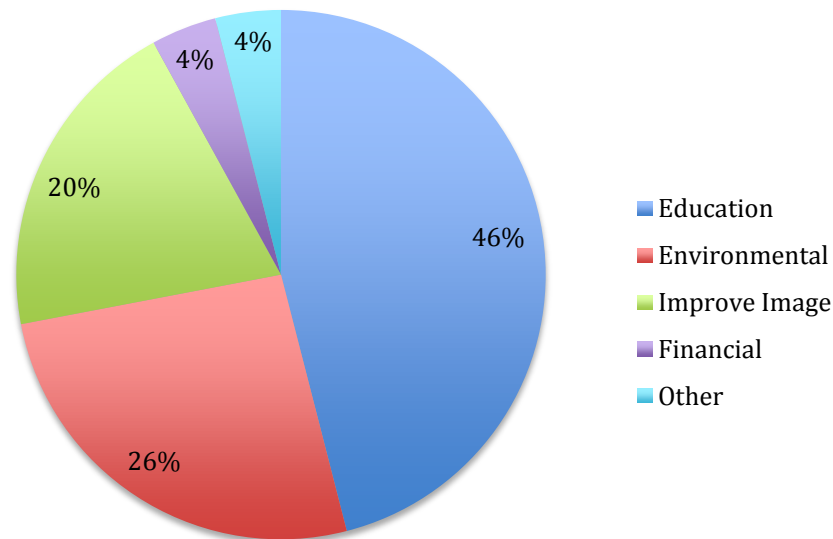
From the interviews with the project managers at Harvard and the Museum of Science, we found that pedestrians and people driving by gave positive reviews of the wind turbines, but residents in nearby buildings were not all pleased. MOS interviewed numerous residents from distant residential complexes prior to installation. They received no objection to the installation and still have not received any complaints. Harvard received mixed reviews from the public and residents in its vicinity regarding their two wind turbines at the Soldiers Field Parking Garage. The project managers mentioned that they received compliments and praise from numerous people who have seen the wind turbines, including drivers on the nearby Massachusetts Turnpike. However, they also received a few complaints from neighboring residents regarding the shadow flicker during the time of the day that the wind turbines were in between the sun and

their windows. Besides flicker, there were no complaints of the aesthetics, noise or vibration from the turbines. However, since none of the installations in Boston are installed on residential buildings, it is not certain if people would complain about these factors in the future.

In speaking with the Massachusetts Audubon Society, we were informed that small urban wind turbines are not a major concern regarding avian activity. Rare and endangered species are uncommon in Boston, while there are a lot of non-native species. However, the Audubon is not concerned with non-native species so there is no concern for deaths. Wind turbines may also interrupt the routes of birds; therefore, a potential installer should avoid known avian nesting and breeding grounds as well as migration routes. Wind turbines provide more of a negative effect to bats. This is mainly due to the pressure difference caused by their rotating blades, and this difference in pressure can damage the lungs of bats. Despite danger posed by the spinning turbine blades on bats, there is currently very little information and research into this issue.

#### 4.4.2 Social Motivations for Installing Rooftop Wind Turbines

During our research in Boston, we noticed that many rooftop wind turbines were not installed for power production purposes. In fact, the existing rooftop wind turbines have been installed mainly for educational purposes or to demonstrate a commitment to renewable energy. This is supported by an article from the United Kingdom, which illustrates the different motives people had for installing urban wind turbines. These motives are seen in Figure 16.



*Figure 16 - Reasons for installing urban wind turbines (used with permission from Syngellakis, Robinson, & Carroll, 2006)*

From this information it shows that education is currently the most prominent reason for installing urban wind turbines, followed by environmental reasons and improving the image of an organization. They were barely considered for financial gain.

From our interviews with project managers in Boston, this information was confirmed to an extent. Only a few of the installed rooftop wind turbines are producing enough energy to make a

noticeable difference in the energy consumption of their corresponding building. Organizations have installed rooftop wind turbines for other reasons, including demonstration and education. The Holyoke Center at Harvard University in Cambridge is one example of this motive. We were told that this array of 1kW wind turbines is purely a demonstration of Harvard's commitment to renewable energy. This display of commitment may make a good impression for an organization, even if it involves taking a financial loss. Rooftop wind turbine installations can also provide a means to motivate others to pursue renewable energy.

Another rooftop installation with a similar motivational purpose is a 1.9kW wind turbine on the roof of Boston City Hall. When we spoke with someone at City Hall, they told us that the turbine is not connected to the grid, but instead a light bulb. Since it is on a well-known government building in a socially active area, it is possible that it will have a large social impact by helping wind power become known as a renewable source and making a good name for the local government.

With the current lack of knowledge about the performance of small urban and rooftop wind power, education is another purpose for rooftop wind turbines. The Boston Museum of Science is one such example, as they have five different types of wind turbines on their roof. This was done to gain further information about the rooftop potential of current wind turbine models. Each wind turbine has been monitored since they were installed and the collected data is available to the public.

With improving research and technology in the small wind energy field, many improvements could be made to make rooftop wind more efficient. More efficient wind turbines could lead to more installations and an increased awareness and knowledge of small wind. This information is a key part of determining the current and future feasibility of rooftop wind turbines. However, social support or opposition can be the deciding factor, especially when it influences the opinion of the stakeholders that might install the wind turbines.

## 5 Conclusions and Recommendations

This chapter summarizes our results and presents recommendations regarding rooftop wind turbines in Boston. First, we make the case that rooftop wind turbines are currently not feasible in Boston, primarily due to the low capacity factor typical in urban environments. Next, we argue that the capacity factor may change due to improved siting or use of VAWTs instead of HAWTs, and we suggest several siting criteria for rooftop wind turbines. Finally, we recommend areas of research and development that the DOER can look into in order to work towards a future where rooftop wind turbines are feasible in Boston.

### 5.1 Conclusions

**The primary factor limiting the feasibility of small wind turbines is the low capacity factor in an urban environment.**

Out of the many studies we found, the average capacity factor for rooftop wind turbines was 5%, with the highest being 14%. This suggests that a good site can achieve at least 14%, and can likely achieve an even greater capacity factor considering that small rural wind turbines have an average of 20-35%. Additionally, improvements in technology could also increase this capacity factor even further, especially for VAWTs, which are currently behind HAWTs in terms of research. This poor performance is currently a major factor restraining the feasibility of small urban wind turbines and can be accounted for mostly in the siting of the wind turbines. An urban environment offers wind that is for the most part turbulent, and careful siting is required to avoid this turbulence.

**A combination of increased capacity factor, price of electricity, and/or value of RECs could make rooftop wind turbines more economically feasible in Boston in the future.**

The low capacity factor achieved in an urban environment is the main hindrance in rooftop wind turbine feasibility; however, it is not the only factor affecting it. The price of electricity and cost of RECs also affect how much income is generated from energy produced with a wind turbine. These three factors have the largest affect on the economic feasibility of rooftop wind turbines. Using realistic values for these factors in the present, we were able to conclude that small increases in each of them could significantly reduce the payback period of rooftop wind turbines, making them more economically feasible. The current scenario is shown below along with this optimistic future scenario.

	Capacity factor	Price of electricity	Value of RECs	Annual production	Payback period
Current	15%	16¢/kWh	\$30	17MWh	14.1 years
Future	25%	18¢/kWh	\$35	29MWh	7 years

*Table 11 - Current and future economics overview*

**Certain areas and buildings types are particularly promising for rooftop wind turbines.**

We came up with several criteria that can help narrow down potential wind turbine sites, and applying these to Boston we have found that the financial district and waterfront area are both sites with good potential. The criteria we developed suggest that a potential building should be:

- Above 150 feet tall
- Have a roof at least 5,000 square feet
- Supported by columns which the turbine can be attached to
- Taller than buildings upwind
- Not in a historic district
- Not in or near an avian habitat
- Connected to either a spot or radial network
- Preferably commercial, waterfront, or industrial area

**Turbine power ratings and power curves provided by manufacturers do not always match real-world values due to a lack of standards for reporting such data.**

Many studies have shown that real-world data from small wind turbines does not always agree with the power curves and ratings provided by wind turbine manufacturers. This makes choosing turbines challenging, since it is difficult predict performance. This inconsistency is due in part to the lack of any standardization process or third party verification of the data provided by manufacturers. If standards were created, and an organization were to test the claims regarding small wind turbine power curves and ratings, choosing turbines and predicting potential energy output would become much easier and accurate.

**Current NSTAR regulations and practices pose a barrier to the installation of rooftop wind turbines.**

Connecting a wind turbine, or any form of distributed generation, to the electrical grid is currently somewhat complex. In an urban area, where spot and area networks are common, there are several difficulties encountered when connecting a wind turbine to the grid. NSTAR is more concerned with providing consistently reliable service to their customers than they are with accepting DG sources onto their network. Because of this, NSTAR sets limits that allows for easier permitting if the DG is under 25kW and produces no more than 15% of the building's minimum load. However, NSTAR is currently working to make their electrical networks less of a barrier to DG, so the problems that exist now may become less of an issue in the future.

## **5.2 Recommendations**

**We recommend that the DOER perform testing on small wind turbines, especially VAWTs, to determine their performance in urban environments.**

Currently, there is little information on the performance of wind turbines in urban environments, especially VAWTs. While some studies have addressed the issues of performance and capacity factor in urban settings, they don't discuss what causes the low capacity factors, or suggest ways to achieve a higher capacity factor. This is especially the case for VAWTs in urban environments, since they have far greater variation in design than HAWTs. If the DOER were to test the performance of small wind turbines in urban environments, they could determine the siting features that would provide a higher capacity factor and make rooftop wind turbines more feasible. We recommend that the DOER collaborate with the CADMUS group and renewable energy research agencies in Europe, such as the Swedish Centre for Renewable Electric Energy Conversion to further investigate the urban use of small wind turbines, and in particular VAWTs.



**We recommend that the DOER provide assistance to individuals or organizations interested in installing rooftop wind turbines by helping them locate and assess potential sites.**

Proper siting for a wind turbine can be a daunting process to tackle, especially for individuals attempting it for the first time. The DOER can offer much to help find proper sites within Boston, with the help of the siting map we have provided with overlapping layers that pertain to various siting factors such as wind speeds, zoning, and network types. The siting criteria we provide in the findings can also be used for siting of a rooftop wind turbine. This can lead to more successful wind turbine installations in Boston, increasing the number of turbines that can be studied as well as getting the public more acquainted to rooftop wind turbines.

**We recommend that the DOER maintain an international database of all the small wind turbines available.**

Such a list would prove valuable in selecting wind turbines for potential projects and research. Additionally, an updated list would help determine which manufacturers are out of business, which is important to know in an industry that changes as quickly as wind power. This list could be built from our database of small wind turbines, and start with the same sources we used, which can be found in our database. Unlike some of the databases and online listings, this database should provide international models, since many of these perform better than US models. It would also be helpful if this database is accessible online, so potential installers could easily locate a turbine that would adequately suite his or her needs.

**We recommend that the DOER work with the Small Wind Certification Council and other international organizations to develop a standardized method of establishing and verifying power ratings and power curves.**

Currently, power ratings and power curves do not have a standard method of being established, and there is no verification process by third parties. Since these are the most important indicators of how much energy a wind turbine can be expected to produce, a standard is needed to allow turbines from different manufacturers to be compared accurately. This could benefit alternative energy developers by providing a reliable way to measure wind turbines' potential output against one another, allowing them to be more accurately analyzed and sorted.

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## **Appendix A: Generator Types and Efficiency**

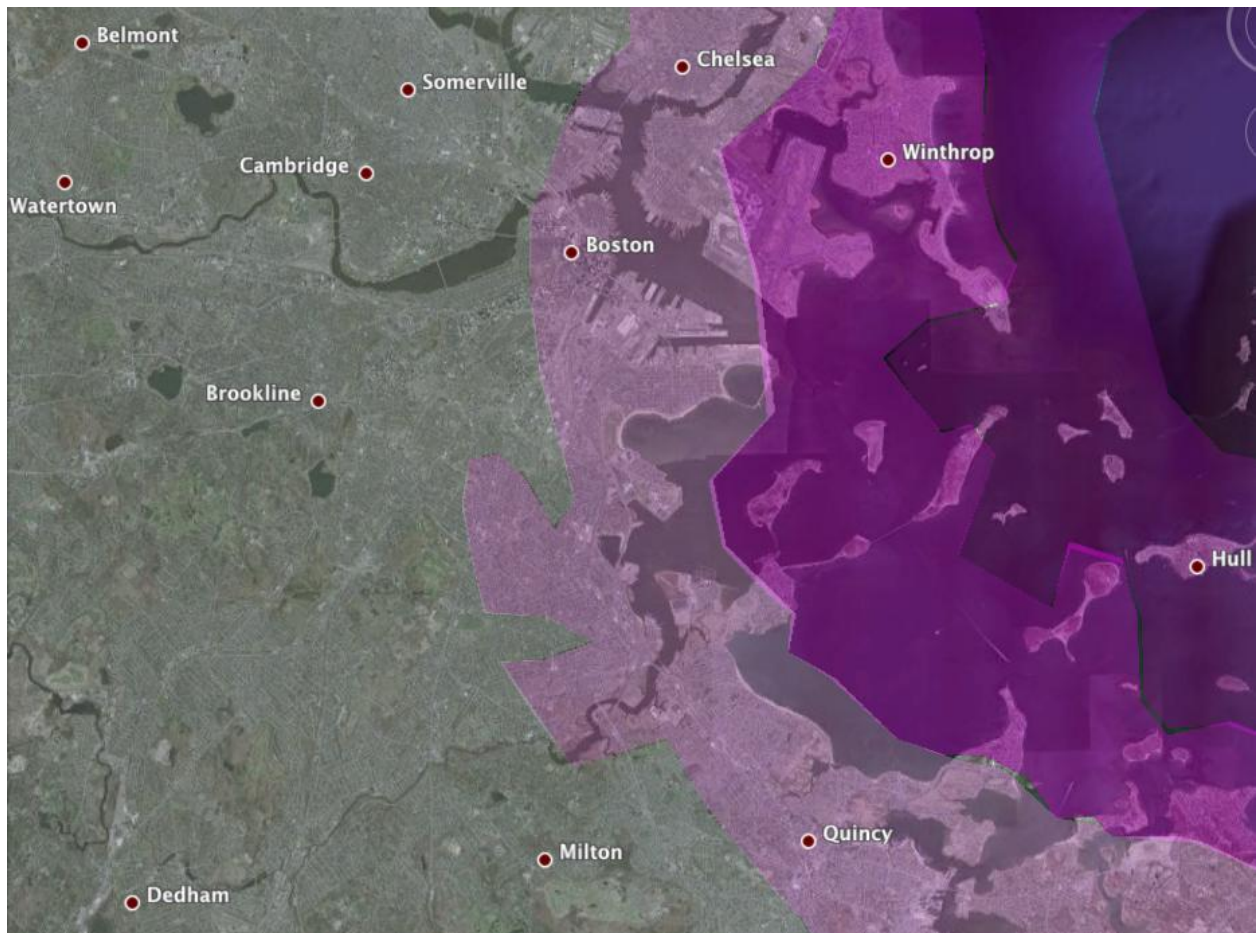
DC generators were originally used in most small wind turbines since their speed can be easily controlled. However, most DC generators lose efficiency due to the use of brushes on the inside of the generator. Brushes are conductive and function as a means of outputting the energy that is induced in the windings of the generator's rotor. Brushless DC motors exist and are more ideal, but because of the limitations on the permanent magnet, they are only used for ratings under 100kW (Patel, 2006, pg.89).

The synchronous generator is a type of AC generator and works at a constant speed based on the input frequency. Thus, this tends to be inefficient with variable wind speeds. The biggest advantage of the synchronous generator is the fact that they are highly efficient and can be directly connected to the grid since they do not require reactive power from the grid. Reactive power is essentially an unwanted element in power distribution and active power is preferred. Permanent magnet synchronous generators (PMSG) offer the highest efficiency and have a high torque at low speed and are therefore suitable for small-scale designs. While small-scale designs have a lower operating and maintenance cost, the cost of magnet material is an issue with large-scale designs (Baroudi et al, 2006).

Finally the induction generator is the most used AC generator for large wind turbines. This type of generator can be used in situations where wind velocity is constantly fluctuating. This system has a rugged brushless construction that has a low capital cost, low maintenance and better transient performance. Also the generator works well at varying speeds, which is perfect for small wind turbines.

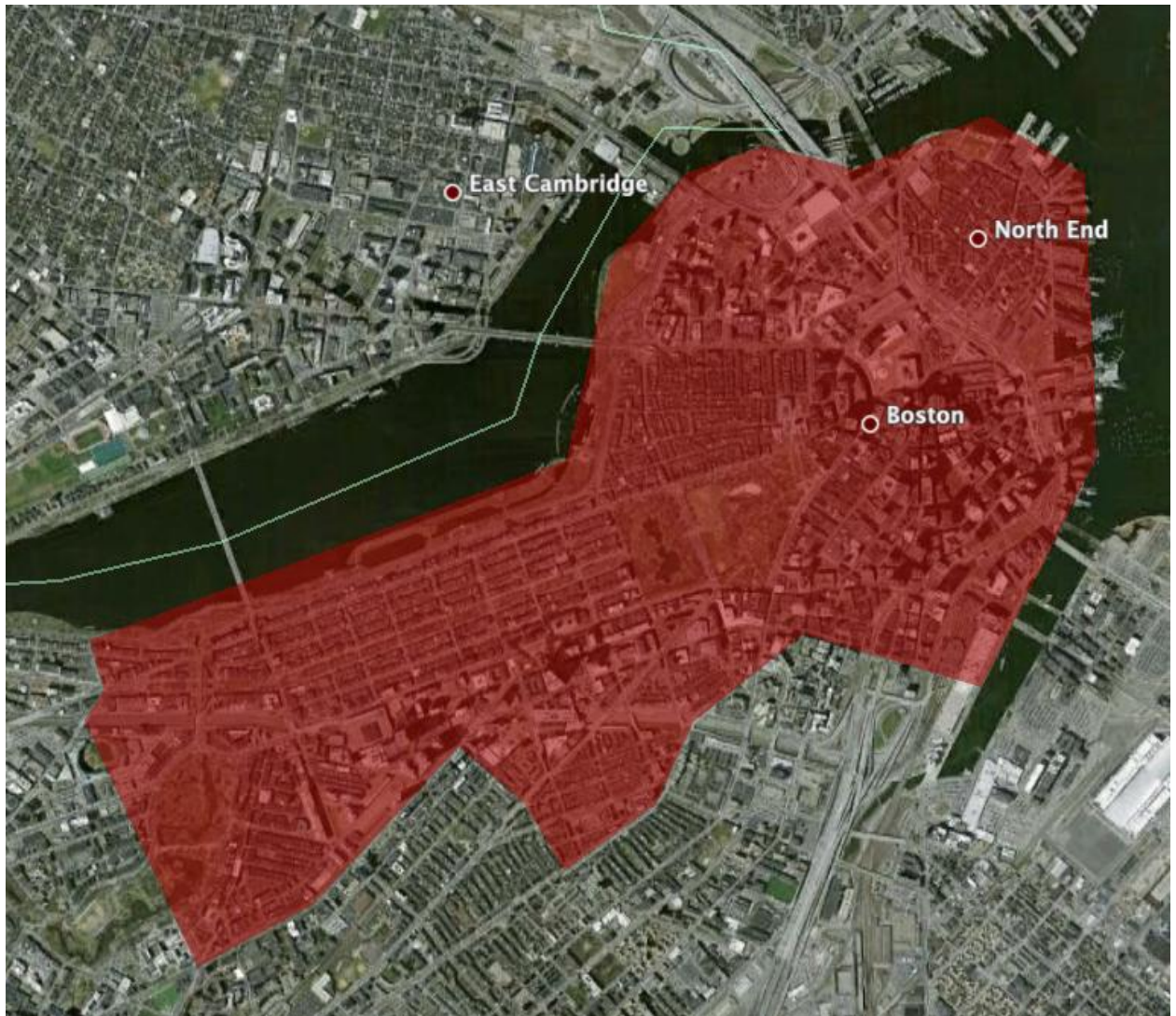
## Appendix B: Siting Map Layers

Enclosed in this appendix are the different siting layer that are in our siting map: wind speeds at 70 meters, grid types, historical areas, avian habitats, preferred zoning areas, and current wind turbine installations. These layers were formed using Google Earth.

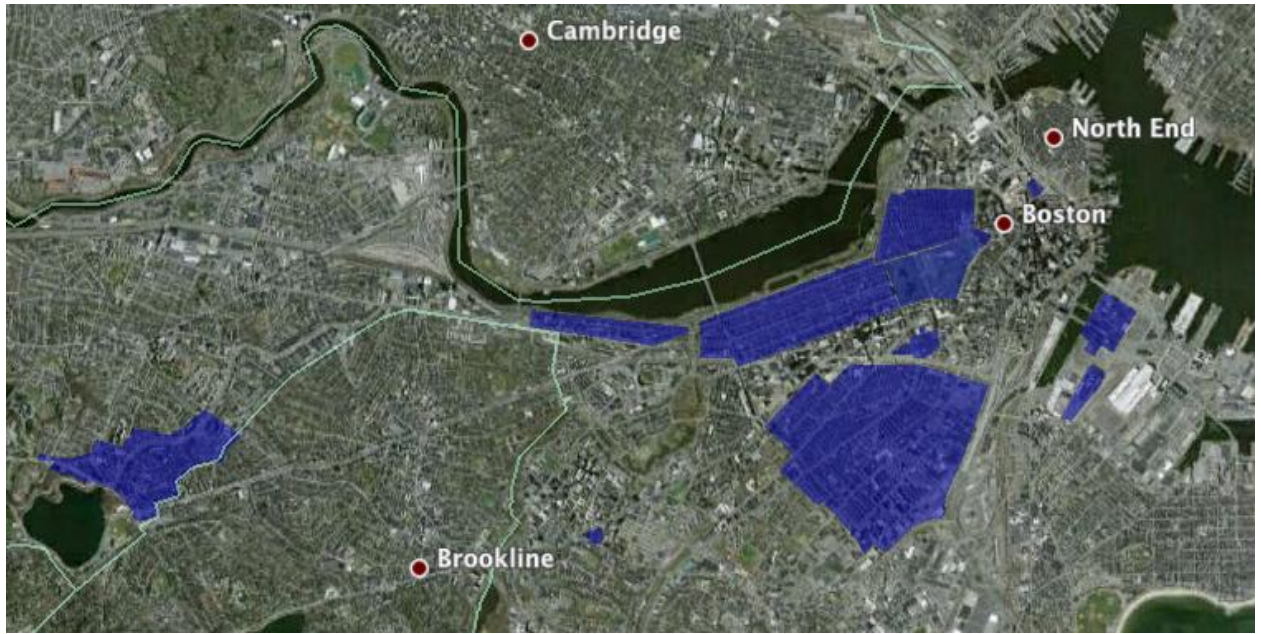


Wind Speeds at 70m





Area Network

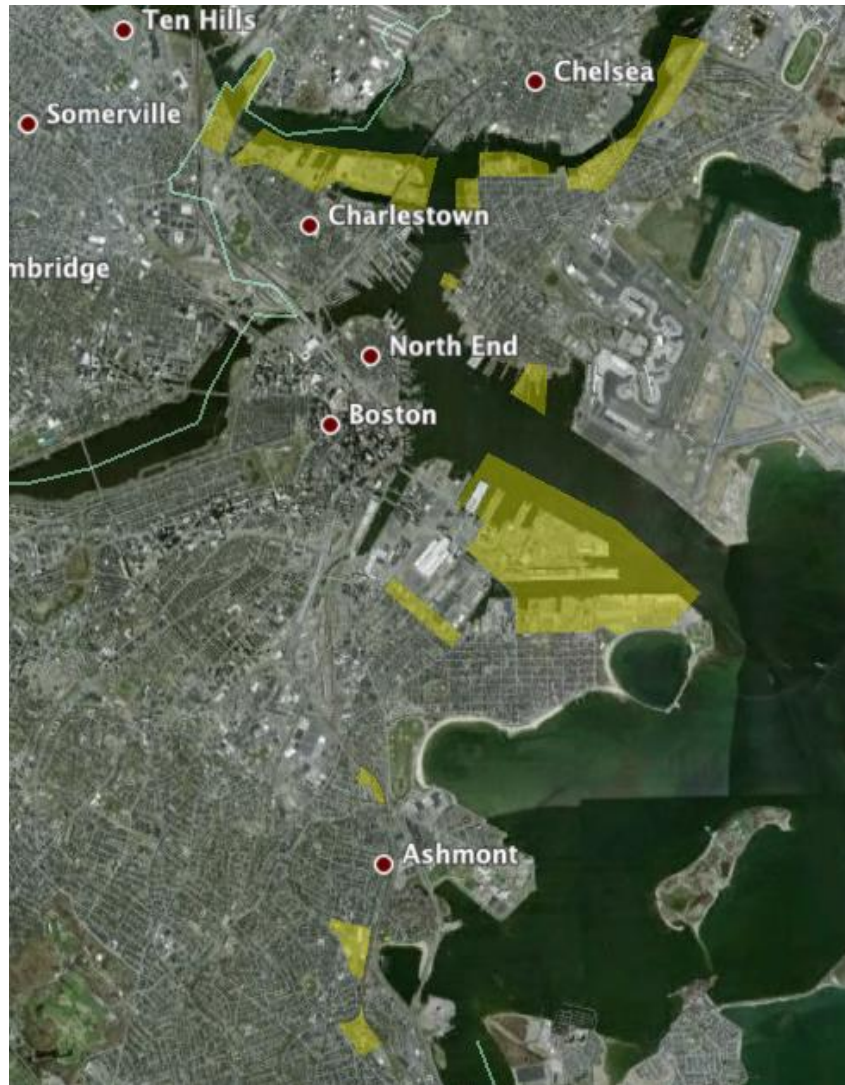


Historical Areas





Avian Habitats



Preferred Zoning Areas



Wind Turbine Installations

## Appendix C: Wind Turbine Models

Manufacturer	Model	Location	Rated Power (kW)	Cut-in Speed (mph)	Rated Production Speed (mph)	Survival Speed (mph)	Blade Diameter (ft)	Weight (lbs)	Mast Height (ft)	Noise (dB@ ms)	Turbine and Tower Cost (USD)	Product Life (years)
<b>VAWT</b>												
Aeolos Wind Energy	Aeolos-V 5000w	UK	5	6.7	24.5	111.5	13.1	814.0	12.5			20
Aeolos Wind Energy	Aeolos-V 10kw	UK	10	6.7	24.5	111.5	19.7	1,364.0	21.6			20
Century Wind Energy	CWE-V-P5000	US (KY)	5	6	24	111	13	2167.0	18		\$24,600	15
Enviro Energies	5 kW MVAWT	US	5	4	29	120	14	1,921.0	8	<20	\$27,990	20
Enviro Energies	10 kW MVAWT	US	10	4	31	120	20	305.0	10	<20	\$51,990	20
Gual Industrie	Statoeolien GSE 8	France	6	4.5	34	134	26.25	5,500.0	9.84			
Ropatec AG	Big Star	Italy	20	6.7			26.25	7,937.0	14.11			
Ropatec AG	Maxi	Italy	6	6.7			15.42	1,676.0	8.2			
UrbanGreenEnergy	10kW	US (NY)	10	4	12			6600		37@10		
Venco Power GmbH	Vertikon H50	Germany	50	5.6	26.8	112	39.37		41.01			
WePower	Falcon 5.5	US (CA)	5.5	6	29	111	15	2,167.0	18	32@6.7@9ft		
WePower	Falcon 12	US (CA)	12	6	29	111	20	4,190.0	18	32@6.7		
Windports	Windports 5kW	Canada	5	5.6	32.44	124	14.44	2,205.0	13.55			30
Windports	Windports 10kW	Canada	10	5.6	32.44	124	14.44	4,211.0	22.31			30
Windports	Windports 20kW	Canada	20	5.6	32.44	124	14.44	8,157.0	44.62			30



HAWT (7-25 ft diameter)												
A&C Green Energy	Talon 5	US (TX)	5	6.7	23	112	18.37	750			\$12,984	15
A&C Green Energy	Talon 10	US (TX)	10	6.7	24.6	112	25	1102			\$27,041	15
Abundant Renewable Energy	ARE442	US (OR)	10	6	25		23.6	1,650.0	43 - 106			
Manufacturer	Model	Location	Rated Power (kW)	Cut-in Speed (mph)	Rated Production Speed (mph)	Survival Speed (mph)	Blade Diameter (ft)	Weight (lbs)	Mast Height (ft)	Noise (dB@ ms)	Turbine and Tower Cost (USD)	Product Life (years)
Aeolos Wind Energy	Aeolos-H 5000w	UK	5	6.7	22.3	100.7	16.4	396.8		31@5		30
Aeolos Wind Energy	Aeolos-H 10kw	UK	10	6.7	22.3	100.7	24.6	925.9		34.5@ 5	\$26,760	30
Aircon	Aircon 10	Germany	9.8	5.6		116	22.72					
Altem Power	APL10	India	10	5.6	24.6		24.6	1,543				
Aquitaine AeroGenerateurs	WM-5000	France	5	6.7	24.6		16.4					20
Aquitaine AeroGenerateurs	WM-10000	France	10	6.7	24.6		23					20
Braun Windturbinen GmbH	Antaris 5.5 kW	Germany	5.5	4	15.7		14.4	110.2				
BroadStar*	AeroCam Type I	US (TX)	10	4	30	140	10		80, 100, or 120		\$30,000	20
Century Wind Energy	CWE-FRE-5KW	US (KY)	5	6	16	111	16.4	1980	39		\$19,000	15
Century Wind Energy	CWE-FRE-10KW	US (KY)	10	4	23	111	23	6325	52.5		\$37,000	15

Eagle Windpower	Eaglepower 5	Finland	5	4.5	20	111.8	19.7	507	138			
Eagle Windpower	Eaglepower 10	Finland	10	4.5	20	111.8	23	2204	138			
EC Industry Group	5kW	China	5	5.6	22.4	110.7	21	835.6	138			
ElectroSfera	breeze 5000	Russia	5	6.71	26.8	112	16	506	44.8		\$15,847	20
EolPower	EOL-H-5	Italy	5	5.6	20		19				\$21,812	20
First Renewable Energy Group	Windworker-5000H	China	5	4.4	22.4		16.4		40			20
First Renewable Energy Group	Windworker-10000H	China	10	4.4	22.4		23		52			20
Fortis	Alize	US (NY)	10	4.5	24.6		23	847.0	80		\$31,100	20
Fortis	Montana	US (NY)	5.8	6.7	24.6		16.4	440.0	80		\$15,800	20
Manufacturer	Model	Location	Rated Power (kW)	Cut-in Speed (mph)	Rated Production Speed (mph)	Survival Speed (mph)	Blade Diameter (ft)	Weight (lbs)	Mast Height (ft)	Noise (dB @ ms)	Turbine and Tower Cost (USD)	Product Life (years)
Franklin Wind Energy	H-10	US (MI)	10	7	26		20	450	65.6			
Hannevind	Hannevind 5.5 kW	Sweden	5.5	4.4	20		19.7	330	49			20
Hummer	Hummer 5	US (IN)	5	5.6	22		21	1,214.4	80	34@5	\$11,393	20
Jetpro Technology	JPS-5KW	Taiwan	5	6.7	26.8		9.8	661.4				
Proven Energy	Proven 11	United Kingdom	6	5.6	26.8	156.6	18	1,322.0	25.9 or 49.2	40@11 , 65@44	\$30,013	20
Qingdao ZiCheng Wind Generator	5kW	China	5	6.7	24.6		19.7		29.5			
Renewable Engineered Systems	Air Wind Power 5000	US (VA)	5	6.7	22.4		21					

Solicity Inc.	Eoltec Scirocco	Canada	6	6	25	135	18.4	450.0				
Suneco Green Energy	ECO-5kW	China	5	6.7	24.6	111.8	16.4	771.6				
Suneco Green Energy Tairui	ECO-10kW	China	10	5.6	24.6	111.8	23	2,160.5				
Windpower Co.,Ltd	TR6.4-5000W	China	5	4.47	22.4	101	20.48		38.4			
TechnoSpin	TSW 4000	US (NY)	4	5.6	26.8	123	13.8	385.0				
TechnoSpin	TSW 8000	US (NY)	8	5.6	26.8	123	22		40			30
TechnoSpin	TSW 13000	US (NY)	13	5.6	26.8	123	22		40			30
Ventera Energy	VT10-240	US (MN)	12	6	29	130	22	500.0				
Ventera energy corp	Ventera VT-10	US(MN)	10	6	29	130	22	500	50-130		\$12,000	20
West wind	5kW Westwind	Ireland	5.5	6.71	31.3		16.32	440				
West wind	10kW Westwind	Ireland	10	6.71	31.3		19.54	836				
Wind Simplicity	Windancer7	Canada	7	2.2			9.8	846.6				
Wind Simplicity	Windancer23	Canada	22.8	4.5			12	1,735.0				
Windeco	Vento 5000	Spain	8	4.47		93.2	16	440	38.4			
Zhuhai Hong Feng	Airforce 4.1	China	5	7	27	134	13.4	209.4			\$12,500	20
Manufacturer	Model	Location	Rated Power (kW)	Cut-in Speed (mph)	Rated Production Speed (mph)	Survival Speed (mph)	Blade Diameter (ft)	Weight (lbs)	Mast Height (ft)	Noise (dB@ ms)	Turbine and Tower Cost (USD)	Product Life (years)
<b>HAWT (26-50 ft diameter)</b>	(Category)						1				\$10	1
A&C Green Energy	PowerMax+ 20	US (TX)	20	6.7	26.8	112	32.8	3911			\$64,916	15
A&C Green	PowerMax+	US (TX)	25	6.7	26.8	112	32.8	4002			\$80,186	15

Energy	25											
Aeolos Wind Energy	Aeolos-H 20kw	United Kingdom	20	6.7	22.3	100.7	32.8	903.0		35@5	\$51,230	30
Aeolos Wind Energy	Aeolos-H 30kw	United Kingdom	30	6.7	22.3	100.7	41	3,042.3		41.5@5	\$70,820	30
Aerofortis Energy	AF-9500N	Taiwan	9.5	5.6	28		29.5					
Aerostar	Independence 30	US (MA)	30	8	30		41.3	3,850.0		44@15		
Aquitaine AeroGenerateurs	WM-20000	France	20	6.7	24.6		32.8					20
Aventa Ltd	AV-7 LoWind	Switzerland	6.5	4.47	13.4		41.28	2831.4	57.6	<30dB at 50m		
Century Wind Energy	CWE-FRE-20KW	US (KY)	20	5	33	111	33	8932	59		\$48,000	15
Eagle Windpower	Eaglepower 20	Finland	20	4.5	20	111.8	39.4	4,409			\$62,000	20
EC Industry Group	10kW	China	10	4.5	22.4	110.7	26.2	990			16478-21736	
EC Industry Group	20kW	China	20	4.5	26.8	110.7	32.8	2,769			25184-30882	
First Renewable Energy Group	Windworker-20000H	China	20	4.4	24.6		32.8					20
Hannevind	Hannevind 11 kW	Sweden	11	4.4	20		32.8	771				20
Hannevind	Hannevind 15 kW	Sweden	15	4.4	20		32.8	881				20
Hannevind	Hannevind 22 kW	Sweden	22	4.4	20		42.7	1433				20
Hannevind	Hannevind 30 kW	Sweden	30	4.4	20		42.7	1543				20
Hummer	Hummer 10	US (IN)	10	6.7	22		26.5	2,149.4	80	34@5	\$60,000	20
Hummer	Hummer 20	US (IN)	20	6.7	22		29.5	3,982.0	80	34@5	\$80,000	20

Manufacturer	Model	Location	Rated Power (kW)	Cut-in Speed (mph)	Rated Production Speed (mph)	Survival Speed (mph)	Blade Diameter (ft)	Weight (lbs)	Mast Height (ft)	Noise (dB@ ms)	Turbine and Tower Cost (USD)	Product Life (years)
Jetpro Technology	JPS-50KW	Taiwan	50	6.7	29		28.9	8,818.5				
Nanjing Supermnn Industrial	LS-10kW	China	10	6.7	22.4	111.8	26.2	1,322.8	39.36		\$100,294	20
Nanjing Supermnn Industrial	LS-15kW	China	15	6.7	22.4	111.8	36	1,499.1	49.2		\$18,676	
Nanjing Supermnn Industrial	LS-20kW	China	20	6.7	26.8	111.8	39.4	1,543.2	59.04		\$25,000	
Nanjing Supermnn Industrial	LS-30kW	China	30	6.7	26.8	111.8	41	2,094.4	59.04		\$67,647	15
Nanjing Supermnn Industrial	LS-50kW	China	50	6.7	26.8	111.8	42.7	2,160.5				
Qingdao Long Teng Energy	LT10-20KW	China	20	8.9	26.8	111.8	32.8	9,215.0				
Qingdao ZiCheng Wind Generator	10kW	China	10	6.7	22.3		26.2		39.4			
Qingdao ZiCheng Wind Generator	20kW	China	20	6.7	22.3		32.8		59			
Renewable Engineered Systems	Air Wind Power 10000	US (VA)	10	6.7	22.4		26.2		65-150		\$22,500	20
Renewable Engineered Systems	Air Wind Power 20000	US (VA)	20	6.7	26.8		40		65-150		\$45,000	20
Suneco Green	ECO-20kW	China	20	6.7	24.6	111.8	36	2,160.5				



Energy Tairui Windpower Co.,Ltd	TR8.0-10KW	China	10	4.47	22.4	101	25.6		38.4	\$11,350	
Tairui Windpower Co.,Ltd	TR10.0- 20KW	China	20	4.47	26.8	101	32		57.6	\$18,670	
Tairui Windpower Co.,Ltd	TR12.0- 30KW	China	30	4.47	28	101	39.36	2,640.0	59.04		
Wind Turbine Industries	Jacob 31-20	US(MN)	20	8	26	12i0	31	2500	80-120	\$55,225	20

## Appendix D: Wind Speed at Different Elevation Calculation Method

To calculate the wind speed at a particular elevation, one must first have wind speeds at a lower elevation. These lower wind speeds were attained from maps of average wind speeds in Boston, and we then used several equations to estimate the speed of the wind at a given elevation. The equations can be found at “[http://en.wikipedia.org/wiki/Wind\\_gradient](http://en.wikipedia.org/wiki/Wind_gradient)” and “<http://www.sustainableenergyworld.eu/calculate-windturbine-annual-energy>.”

The first equation is:

$$v_w(h) = v_{10} \cdot \left(\frac{h}{h_{10}}\right)^a$$

$v_w(h)$  = velocity of the wind at height  $h$

$v_{10}$  = velocity of the wind at height  $h_{10} = 10$  meters

$a$  = Hellman exponent

Where the Hellman exponent depends upon the costal location as well as the shape of the terrain on the ground. The value of the Hellman exponent can be found via a table taken from [http://en.wikipedia.org/wiki/Wind\\_gradient](http://en.wikipedia.org/wiki/Wind_gradient)

Location	$\alpha$
Unstable air above open water surface:	0.06
Neutral air above open water surface:	0.10
Neutral air above flat open coast:	0.16
Unstable air above flat open coast:	0.11
Stable air above open water surface:	0.27
Unstable air above human inhabited areas:	0.27
Neutral air above human inhabited areas:	0.34
Stable air above flat open coast:	0.40
Stable air above human inhabited areas:	0.60

For our analysis, we used a Hellman exponent of 0.6.

The second equation is:

$$v_h = v_{10} \cdot \log(h/z) / \log(10/z)$$

$v_h$  = windspeed at height  $h$

$v_{10}$  = windspeed at a height of 10 meters

$z$  = roughness length of the site

Where the roughness length can be found based on values from

“<http://www.sustainableenergyworld.eu/calculate-windturbine-annual-energy>.”

Location	Roughness Length
Ice, water surface:	0.001
Grass, airports:	0.03
Trees, hedgerows, scattered buildings:	0.2
Rough terrain:	0.25
Villages, very rough terrain:	0.5
Cities, forests:	1
City center, skyscrapers:	2

For our analysis, we used a roughness length of 2.

## Appendix E: Economic Analysis Methods

We have the initial data:

1. Expected Lifetime, in years (L):
  - a. An estimate of how long a wind turbine will last before it no longer produces energy.
2. Turbine Cost (\$USD): C
  - a. The cost of the wind turbine and the pole it will be mounted on.
3. Installation Cost (\$USD): A
  - a. All costs involved in securing the wind turbine and pole onto the roof.
4. Cost of Electricity (\$/kWh): E
  - a. Cost the user pays to their electric utility provider for each kilowatt-hour.
5. Cost of Maintenance (\$USD/year): M
  - a. All costs involved in any yearly maintenance or upkeep of the wind turbine.
6. Rate of Inflation (%): I
  - a. The amount by which US currency loses value against the cost of commodities.
7. Electricity Produced (kWh/year): P (calculations can be found in section 4.2)
  - a. The number of kilowatt-hours the wind turbine is estimated to produce in the first year.
8. Government Incentives
  - a. Price Per REC: Ppr (1 REC is earned per MWh generated)
  - b. Production Tax Credit: Ptc (\$0.21/kWh)
  - c. Federal Investment Tax Credit: Fitc (30% of initial costs)

The assumptions we made were:

1. Installation is 80% of the cost of the turbine
  - o We assumed this after interviews with wind turbine installers and project managers of wind turbine installations in Boston. It should be noted that installation costs vary largely with the specific building the turbine is being installed on.
2. Turbine produces 0.20% less energy each year
  - o Even though there is a yearly maintenance fee, wind turbines are physical devices, and not all wear can be repaired, so a very small percent decrease in production is assumed.
3. Electricity costs 16¢/kWh
  - o This was the average cost of electricity in Massachusetts at the time this report was written.
4. Yearly maintenance is \$100
  - o This cost covers all yearly fees, which should be low, as nearly all manufacturers claim that their turbines only require a visual inspection once a year.
5. Inflation is fixed at 2%
  - o This value is fixed at a standard percent for economic calculations with a fixed inflation rate. However, it should be noted that inflation is heavily dependent on the current state of the economy, and can see large changes over time.
6. RECs are fixed at \$30/REC
  - o This was the cost per REC from wind at the time this report was written.

Unmodified **initial costs** =  $C + A$

**Initial costs** minus government incentives =  $(C + A) - Mwi - Fitc$

Initial **net present value** =  $Mwi + Fitc - C - A$

First year's **net income** =  $[(P * E) + (P * Ptc) + [(P / 1000) * Ppr] - M] * (100\% - I)$

**Net present value** after first year = Initial minus government Incentives – First year's income

**Net income** for each year after first = **Net income** from previous year +  $[(P * E) + (P * Ptc) + [(P / 1000) * Ppr] - M] * (100\% - I)$

**Net present value** each year thereafter = Total **net present value** + **Net income** from previous year

## Appendix F: Districts in Boston Allowing Rooftop Wind Turbines

The following is taken directly from Article 88 of the *Boston Zoning Code and Enabling Act*:

“Building integrated wind energy facilities are allowed in the following districts and subdistricts:

- I - General Industrial
  - MER - Maritime Economy Reserve
  - W - Waterfront Industrial
  - WM - Waterfront Manufacturing
- ii. Building integrated wind energy facilities are Conditional in the following districts and subdistricts:
- H - Apartment
  - MFR - Multifamily
  - MFR/
  - LS - Multifamily/ Local Services
  - B - General Business
  - CC - Community Commercial
  - M - Restricted Manufacturing
  - IDA - Industrial Development Area
  - LI - Local Industrial
  - EDA - Economic Development Area
  - IS - Institutional
  - LIA - Logan International Airport
  - WS - Waterfront Service
  - EPS - Enterprise Protection Subdistrict
  - OS - Open Space
    - Boston Harbor Islands
  - CUF - Cultural Facilities (Fenway)
  - CF - Community Facilities
  - NI - Neighborhood Institutional
  - CPS - Conservation Protection Subdistricts
  - Harborpark District, with the exception of those districts and subdistricts listed as Allowed in Section 88-5.3(a)i.
  - Midtown Cultural District
  - North Station Economic Development Area
  - South Station Economic Development Area
  - Huntington Avenue/Prudential Center District
  - Chinatown District
  - Leather District
  - Government Center/ Markets District
  - Bulfinch Triangle District
  - Cambridge Street North District

North End Neighborhood District  
Audubon Circle Neighborhood District  
Bay Village Neighborhood District  
South End Neighborhood District

Notwithstanding the above, building integrated wind energy facilities are Allowed in any district or subdistrict in the City if such facility is mounted on a building over three hundred (300) feet in height and has a rated nameplate capacity of not more than 6kW.”

## **Appendix G: Interview Questions**

### **Interview Questions for NSTAR Engineers**

1. What issues arise from having different types of generators on the same network?
  - a. How is back-EMF prevented?
  - b. Are there other problems?
2. What are the criteria for distributed generation on spot networks?
3. Why are network protectors a major concern? Poor construction?
4. Is there anything NSTAR is working on that would allow for easier distributed generation?
  - a. IEEE 1547.6
5. Is it possible to find out where the spot or radial networks exist in Boston?
6. What locations would be best for distributed generation?
7. Would any of these locations be ideal for wind turbines?
  - a. General industrial
  - b. Maritime economy reserve
  - c. Waterfront industrial
  - d. Waterfront manufacturing
8. Was there anything that the Museum of Science, Logan Airport, or Harvard University wind turbine projects considered, but wasn't allowed?

### **Interview Questions for Audubon**

1. What are some of the concerns that you have regarding the effects of small wind turbines on local avian populations?
2. Are there any avian sensitivity maps in the US similar to those in Europe that can guide the installations of these turbines?
3. Do you believe wind turbines in urban areas, as opposed to rural areas, would have any significant impact on local avian populations?
4. Do you have any general suggestions for wind turbine placement that might help minimize the impact on local wildlife?



## **Interview Questions for Boston Museum of Science and Harvard**

1. What alternative energy sources had you looked into before you decided on wind turbines?
2. What are the technical criteria that you considered in choosing the wind turbines you used for this project?
3. What sort of siting analysis did you choose, prior to installation?
4. What are some problems you encountered during the project planning? For example: zoning restrictions, connection to the electrical grid, structural integrity issues, etc.
5. What grid connection setup is being used for the rooftop wind turbines?
6. How has the wind turbine performance been like since its installation? How has this compared to its expected performance?
7. What were some of the incentives, if any, you received for this project (federal, state, other)?
8. Was there any initial opposition to the project from any external or internal party? For example: neighbors, historical societies, groups concerned with bird fatalities, etc.

## **Interview Questions for Hines Corporation and Boston Housing Authority**

1. What knowledge do you have, if any, about wind energy? (small scale wind turbines in particular)
2. What kind of buildings do you own? What are some of the uses for these buildings?
3. What types of other buildings are located in the immediate vicinity of the buildings you own? (Skyscrapers, convention center, apartment complexes, etc.)
4. Are there any examples of green energy or wind turbines on or near your buildings?
5. Have you ever thought of incorporating wind energy or other alternative forms of energy production in your buildings? If so, why?
6. How do you think your neighbors would react to the installation of rooftop wind turbines on some of your buildings?
7. If you were to install small wind turbines, what sort of financial assistance would you like to see to help with the costs? (discounts, tax breaks, limited liability, etc)
8. What is the longest payback period you would settle for?
9. Do you have any other concerns about the use of wind turbines as a viable energy source?

## **Interview Questions for Structural Engineer**

Mention static load max per unit is 10,000lbs, and dynamic load range of up to 100-200lbs at 100 mph winds.

1. Can buildings in Boston support these loads?
2. What types of roofs can't support these load?
3. What kind of support is required?
4. What would the rough cost of the support be and how much would it vary based on weight?
5. What are some structural hurdles that should be avoided? (e.g. roofs which aren't flat)

## **Interview Questions for Massachusetts Convention Center**

### **Authority**

1. What knowledge do you have, if any, about wind energy? (small scale wind turbines in particular)
2. What kind of buildings do you own? What are some of the uses for these buildings?
3. What types of other buildings are located in the immediate vicinity of the buildings you own? (Skyscrapers, convention center, apartment complexes, etc.)
4. Are there any examples of green energy or wind turbines near your buildings?
5. Why did you want to use solar panels on the convention center?
6. Have you ever thought of incorporating wind energy in your buildings? If so, why?
7. How do you think your neighbors would react to the installation of rooftop wind turbines on some of your buildings?
8. If you were to install small wind turbines, what sort of financial assistance would you like to see to help with the costs? (discounts, tax breaks, limited liability, etc)
9. What is the longest payback period you would settle for?
10. Do you have any other concerns about the use of wind turbines as a viable energy source?

## Appendix H: Interview Notes

Within this Appendix are the interview notes that were taken for each interview. They are provided in chronological order.

### **NSTAR Interview Notes**

April 1, 2010

Interviewers: Mario Christiner & Ryan Dobbins

#### Spot

- Generator can only produce up to 1/15 of annual load of the building and must have a UL 1741 & IEEE 1547 approved inverter
- For systems which are 25kW or less NSTAR goes with a simplified approval method based on the NSTAR DG tariff

#### Radial

- Tends to be a more costly process to connect to this type of network
- Problem with having a delta transformer and an ungrounded source, which leads itself to synchronous

#### Network Protectors

- Phase angle difference between central and distributed generator is a major issue
- 1-2kW is enough to activate the reverse power relay of network protectors
- Not rated for generator breakers

#### IEEE 1547.6

- Will be validated this year (2010)
- Defines the “de minimis” technique of having a DG of no more than 1/15 of the annual load be connected to the network protector
- Also states how to calculate the load

#### NSTAR DG interconnection tariff

- Gives restrictions on the harmonics and voltage flicker of the DG system
- IEEE 519: Harmonic Specs

#### Projects

- Harvard
  - o Not on network
- Logan
  - o Not on network – ‘customer stations’
- Museum of Science
  - o Connected to grid via inverters

## **Audubon Interview (Phone)**

April 2, 2010

Interviewer: Arnold Ndegwa

The Audubon society is one of the leading non-profit wildlife and habitat conservation organizations in America.

### **Question 1:**

- 2 reactions to the question
  - o Not overly concerned of wind turbines effect on birds except on endangered species and raptors
  - o More concerned with utility scale turbines
- There are a lot of non-native species in urban areas, which are not as much of a concern as local species.
- Bats are actually more of a concern because;
  - o Conservationists don't have a proper amount for the bat population in the area
  - o There is a higher mortality rate in bat populations associated with wind turbines than in bird populations
  - o Bats also have a lower reproductive rate than birds. They normally have one young per breeding bout unlike birds which can have multiple offspring at a time
  - o There is research that suggests bats are attracted to turbines maybe due to
    - Sound
    - Insects attracted to the turbines
    - Not sure if sonar and echolocation used by bats attracts them to turbines
  - o There is also a fungus infecting bats and this causes the white nose syndrome which has been killing bats at an unprecedented rate and thus this is more of a concern currently
  - o There is an indication that mortality lowers with an increase in wind velocity
    - Perhaps because the winds blows the insects away
  - o Tom Canz
    - Boston University ecologist
      - Has more info on bat populations.

### **Questions 2**

- Not sure if we have any sensitivity maps in the US that are presently being used to guide on-shore turbine installations
  - o There is more information on off-shore bird maps
  - o There are however maps showing migrations routes, breeding and nesting grounds etc. that can be referred to

### **Questions 3**

- Not sure due to lack of insufficient data
- There may be no real difference between rural and urban wind turbine installations
  - o Except on migrations routes, resting spots and stops etc.
- Birds normally migrate higher than utility size turbines (i.e. > 450 ft)
- Within the city of Boston, Mt. Auburn cemetery is one of the places wind turbine siting can't occur since birds frequently use it as a stopover.

#### Question 4

- Avoid situations that may put avian populations at risk
  - o Avoid migrations routes
  - o Avoid nesting/ breeding areas
  - o Avoid foraging areas - that may contain prey for raptors
- May not be cost effective to generate specific sensitivity maps
  - o Better to generate broader maps showing wide general areas of breeding grounds, nesting sites and migratory sites.
- The Audubon society has also conducted their own studies on turbine effects on avian populations and they gave the green light to the installations in some small scale turbine installations

Taber Allison was part of a group that drafted guidelines for the Fish and Wildlife Service

- Provides general guidelines regarding all onshore installations
- No plans to amending guidelines to building integrated turbines
- There are however plans to adopt the guidelines to a more local level (Massachusetts level)

**Boston Museum of Science**  
April 6, 2010  
Interviewers: Mario Christiner & Ryan Dobbins

**Siting**

- For wind assessment they used three studies
  - o They used 5 anemometers for one year and used AWS Truewind program to analyze results
  - o Logan comparative study
  - o ANSIS wind flow study
    - SWIFT located in eddy current
- FAA regulations restrict height to 213 feet above sea level
- Manufacturers/Installers sometimes decide they will not conduct installation if too turbulent or not good conditions
- Ice formation was a concern, but not a “deal breaker”
- Show Stoppers (obstacles that make project impossible)
  - o Permitting
  - o Amount of Turbulence
- Other factors we should consider in siting
  - o Public safety/sense of security
  - o Want to be visible for educational purposes
- Dynamic load is more important to consider than static load
- Important siting action is to take anemometer measurement at exact location of turbine hub

**Rooftop Wind Turbine Attributes**

- Focused on models that were commercially available
  - o Disregarded models with lacking information or that are unavailable
- Looked at cut in speed and compared to wind speed availability
  - o Turning at least 75% of the time
- Disregarded models with diameters larger than 20 feet
- For the Proven model the foundation cost was equivalent to the turbine cost

**Reason for Rooftop Wind Turbines**

- First wanted to reduce carbon footprint, but once they started the study phase they soon realized that it was not feasible based on the wind resources, location, and economics.
- Originally thought about hydro and photovoltaic, but wind seemed most controversial, thus the reason they choose it for study

## **Harvard**

April 7, 2010

Interviewers: Ryan Dobbins, Arnold Ndegwa, & John Sivak

### Why wind?

- Harvard has committed to reducing their 2006 electricity needs by 30% by 2016
- This goal has been mainly accomplished with energy efficiency measures, as opposed to energy production
- AeroVironment turbines are purely for visual appeal, showing Harvard's commitment to renewable energy
- Installed as roof was being redone, so that they would age at the same rate as the roof
- Other turbines are Bergey, and are rated for 10kW - average wind speed of 4 to 8 m/s

### Why these turbines?

- Bergey has been in business 30 years
- Turbines are durable
- Low noise
- Collapsing tail for high wind speeds

### Why the location?

- Zoning "The cars won't complain"
- Cambridge side has a lot of historical areas
- No FAA problems
- Mounted the turbines by installing a pillar to hold the weight and dampen the vibration

### Grid connection?

- Disconnect switches within sight of the towers
- Harvard already has stringent electrical codes
- Inverters need to be inside
- Manual reset if a wind turbine shuts down too much
- Real-time measurement system

### Problems?

- No precedent zoning laws
- Several hearings with local stakeholders (historical groups, etc)
- Process took 4 months
- Noise can be amplified by air ducts
- Some complaints of flicker from nearby residents

### Other

- No bat/bird/ice/vibration problems
- Very positive feedback on visual appearance (especially from the Mass Pike)
- Energy production is what was expected
- PV is better -> no maintenance and easier to install
- State Renewable Energy Credits can help cover costs

## **Hines Corporation**

April 7, 2010

Interviewers: Arnold Ndegwa & John Sivak

Hines sells space, so they're interested in what can be done to improve that.

- Usually based purely on payback period
  - Want less than 5 year payback
    - They are however willing to look to the long term and may consider a longer payback period than the above
    - One current exception to the 5 year payback is (heating/cooling plant in Hartford property)
  - Not focused on payback if it is for publicity
    - Would welcome the opportunity to put a demonstration installation to raise awareness
- Tenants also help pay for part of construction fees, although they break even
- Looking at green leases that have special provisions that use sustainability features to promote the building.

Hines owns large high rise buildings, and acquires smaller buildings in suburban areas. Also offer engineering services to others.

- Spend money to upgrade acquired buildings
- Likely zero opposition for high rise buildings
- Small opposition to suburban locations (such as Wellesley Gateway)

Hines doesn't have much information on renewable energy sources, although they have a Conceptual Structural Department that handles that sort of thing.

- If they're improved, wind turbines will definitely be considered by Hines
- There are currently no Hines buildings with rooftop wind turbines but some have PV units installed
  - One property that currently has a PV installation is in times square NY
  - There is a PV/ Geothermal installation planned for Wellesley property

Concerned with structure, vibration, noise, utility connection, and (not so much until it's proved) wildlife



**Structural Engineer (Phone)**  
April 9, 2010  
Interviewers: Mario Christiner & John Sivak

General

- 10,000 lbs works fine
- Trusses, such as in the convention center, can't support large loads

Columns

- Connecting to columns is recommended
  - Might not need as large a foundation
- Can be mounted like a flagpole – exterior column
- One turbine per column, minimum is 4, although you can guess the number of columns from looking at the building (30 feet each direction)
- Large buildings that take up a whole city block (maybe 10 stories in height)

Guides

- Overturning moment can be handled with guy wires
- Depends a lot on the original structure of the building, although guy wires help
- This takes up much more room, although turbines would be placed apart due to wake effect anyway

Roof types

- Cement roofs would be easier for installation
- For metal topped roofs, turbines need to be connected to main structure beneath

Economics

- 20-30% of the cost can be used in mounting. Mainly depends on the weight

## **Massachusetts Convention Center Authority**

April 14, 2010

Interviewers: Mario Christiner & John Sivak

MCCA owns Boston convention center, Hynes convention center and convention center in Springfield. Also leases land to surrounding condos, hotels, and garages.

### **Alternative Energy**

- They have three reasons for considering renewable energy
  - Reduce energy use
  - Goodwill of costumer, who prefer green build
  - Help state market renewable energy, who provides MCCA with funding
- Considered solar thermal, solar electrical and wind
- Solar
  - Conducted a feasibility study, technically feasible, but not financially
- Wind
  - Has been considered, however due to surrounding buildings they believe it would not be feasible
  - Might consider adding to new buildings that will be constructed in the future

### **Economics**

- Public facilities vs. private facilities, public facilities can't benefit from tax rebates and most incentives
- Stimulus package was originally going to be used to fund solar project, however they restricted the aid to water treatment plants and facilities that are likely to be aided for the long run
- Would allow payback period of 10-12 years, but prefer 5-7 years

### **Structural**

- Roof is covered in standing steel metal by BEMOUS, but has been having many leakage issues
  - Required 10 million dollars worth of repair
- Roof is supported by 6 main columns in the middle and tree columns on the side
- Trusses also used to support roof
  - Can support 15,000 lbs every 5 feet

**Boston Housing Authority**  
April 14, 2010  
Interviewers: Ryan Dobbins and Arnold Ndegwa

Question 1

The BHA has looked into wind turbines.

- They looked into the AeroVironment wind turbines even before Logan installed theirs
- They looked into other models of HAWTs and VAWTs
- They also took a look at utility scale wind turbines
- From their investigations, they noticed the low power production of a lot of the wind turbine systems
- They also found no documented proof of efficient power production

Question 2

- They mainly own federal and state public housing
- Their portfolio includes 10% of the affordable housing units in Boston and are indeed the largest landlord in the city
- Have 63 developments with 11-50+ thousand units (depending on how you look at it)
- Their main building types are:
  - 3 story brick walkups (mainly built in the 30s)
  - Newer apartment blocks (built in the 60s and 70s). These are normally between 5-18 floors high and incorporate steel construction
- Their buildings are found all over the city
- Their main use is for residential purposes

Question 3

- Mainly found in residential neighborhoods, therefore most of the surrounding buildings are mainly residential- usually low and mid rise buildings
- However, since it's low income housing, the buildings aren't in the best locations. Some are found right next to commercial and industrial areas

Question 4

- They have some LEED certified buildings that they operate
- In their Maverick Development, there is a LEED certified building with a PV installation
- Every redevelopment that they undertake is made energy efficient
- A new development in Roslindale is being made solar ready
- In their Old Colony project in South Boston, they have a goal of achieving the goal of net zero (total energy self-sufficiency)

Question 5

- They have thought about incorporating wind energy on some properties, but decided that due to siting issues, it won't work on their properties.
- They are always looking to make their buildings greener and more energy efficient as soon as possible through PV installations and LEED certified buildings

Question 6

- Reaction depends mainly on the neighborhood and the visual impact due to the turbine

- There is a visibility issue for some of the taller models
- There is also a zoning issue for historic areas
  - The BHA owns several properties in historic areas of Boston
- The noise changes won't be too much a problem (now more conducive since they measure the decibel level from  $\frac{3}{4}$  mile away instead of the  $\frac{1}{2}$  mile away that it used to be)

#### Question 7

- Main financing options that the BHA is looking into are the grants and rebates
- They already received a grant from the MTC to help with their PV installation

#### Question 8

- The BHA doesn't have a structured payback period
- They are looking toward more of a long time maintenance view
- They also try to look for budget stability as opposed to a for profit organization
  - Hence they want a system to be set up which doesn't have too much maintenance requirements which would lead to lower overall operation cost (out of sight, out of mind)
  - An example of their long term outlook is from one of their contracts. It's a boiler contract that they are expecting to have a 20 year payback period

#### Question 9

- No big concerns about wind turbines
- Waiting for better efficient turbines to come onto the market
- Also acknowledges that proper siting can lower the payback period significantly

#### Other Concerns

It was costly to connect the Maverick PVs to the grid. They therefore use the PV for the buildings power production only and therefore can't sell any surplus back the grid. Co-generation units are more easily accepted by NSTAR for connection to the grid and the BHA is looking to install one through one of its performance contracts.

## **Appendix I: Team Assessment**

Overall our group saw great improvement as the project progressed. We became more open to each other and communicated our ideas in a useful fashion. We used various tools and guidelines to help us perform more proficiently as a whole.

To keep our progress on track, we used schedules. At the start of each week and occasionally at the start of the day we established a schedule of the tasks that we needed to accomplish as a team and as individuals. This made sure that all the required tasks were completed; it also showed if certain individuals were not getting their work done. Along with this we created a list of tasks and distributed these tasks three weeks into the term. We noticed that we had a lot to do, but were all aware of our individual responsibilities. These tasks included the various research, writing and presentations that needed to be accomplished. During a team discussion we established who was responsible for what task.

Mid way through the project, we noticed that people were tardy to work and occasionally handed in late individual work. These were proving to be a hindrance to group progress, so in response, we formed rules of conduct to discourage these actions. The rules worked in such a way to avoid these situations, such as requiring the person who was late to treat the group to lunch. Although it was certainly better to be avoided, when actions did need to be taken, they brought the group together and allowed us to get to know each other more and work better together as a whole. This proved to be an effective method as we only had a few instances of tardiness and late assignments.

In terms of editing the written sections of the report, we were having difficulty revising large documents as a group in a time efficient manner. We set up a system of peer and overall reviews that allowed each person to focus on a smaller section at a time, and then the sections would be rotated. This allowed for closer revisions of each section and was much more time efficient than our previous methods. It also allowed each section to be revised several times by each group member to ensure that it was the best work from the group as a whole. Overall group revision sessions also allowed us to go through drafts and address any comments or concerns.

One main improvement, which required improvement, was sharing work. To remedy this, we set up a meeting after every day of work to discuss what individuals discovered or accomplished that day. These meetings were to keep everyone focused and on track and to stay up to date with any findings that others had. Several of these meetings resulted in improved group communication and knowledge of other group members' progress.

Additionally, we often consulted each other and the advisors when problems arose during the project. We attempted to make the most out of these meetings specifically by creating action items to be followed up on. For example, the advisors suggested that we look at nominal scenarios regarding the performance and economic analyses of wind turbines. Following this, we took their advice and redid all of the calculations based on this better outlook. We were also asked by our sponsor to create an interactive map showing wind speeds and electrical networks to assist with the siting of wind turbines. We completed this map and also went even further by including information on avian habitats, historical areas, and accepted zoning districts to the map.